FACULTY OF PSYCHOLOGY AND EDUCATIONAL SCIENCES
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RISK AND PROTECTIVE FACTORS OF DYSLEXIA: A STUDY OF TEMPORAL AUDITORY PROCESSING AND MORPHOLOGICAL AWARENESS

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Dyslexia is a neurological condition affecting 5-7% of the population, which impacts an individual's ability learning to read and write despite adequate intelligence, education and remediation. The predominant etiological view postulates that dyslexia results from a deficit in the phonological domain, specifically in the quality and accuracy of phonological representations. A vital component in the development of phonological representations is the awareness of individual speech sounds. Recent findings have suggested the existence of an underlying deficit in low-level auditory temporal processing within the dyslexic population. This auditory temporal processing deficit theory hypothesizes that a disruption in the processing of dynamic changes in frequency and amplitude of sounds causes speech perception problems, leading to deviant phoneme representations, ultimately disrupting phoneme-grapheme mappings, which, in turn, is manifest as reading and spelling problems. Such single cognitive deficit models of dyslexia, however, are incapable of explaining all of the expressed behavioural traits observed in a dyslexic population. Additionally, not all individuals with phonological impairments develop dyslexia. This leads researchers to explore a multifactorial aetiology which accounts for multiple risk or protective factors that act probabilistically together to produce the expressed behavioural symptoms of dyslexia.

The aim of this study was to investigate whether children and adults with dyslexia have auditory temporal processing deficits and how these deficits can be characterized. Additionally, within a context of the multiple cognitive deficit model of dyslexia, we aimed to examine the nature and role of morphological awareness (MA) as a unique risk and/or protective factor in literacy outcomes of children and adults with dyslexia. To evaluate developmental and causal influences of both MA and auditory measures, pre-reading children with (HR) and without (LR) a family risk of dyslexia were longitudinally followed up through their early literacy development. Additionally, we examined the nature and expression of these relationships as represented within an adult population with dyslexia.

In an initial study, we investigated whether auditory processing, speech perception and phonological skills contribute to adult reading ability, either independently or conjunctively. Results showed phonological and slow-rate dynamic auditory deficits are related to literacy. Yet, at the individual level the theorized cascading effects of problems in auditory temporal processing could not explain literacy problems. In the same population, we conducted a second study to examine the compensatory role of MA in literacy of adults with dyslexia. MA was found to significantly predict a greater proportion of word reading and spelling within the dyslexic group compared to the controls. While MA deficits were found in adults with dyslexia, compensated dyslexics were found not to differ from controls on measures of MA, implicating intact MA skills being utilized in their achieved reading compensation.

Our remaining studies investigated the nature and development of the auditory temporal processing deficit and early MA of children with dyslexia. In a group of HR and LR pre-reading children, study 3 examined the relation of phonological awareness (PA) with auditory processing and MA prior to formal reading instruction. Results demonstrated an MA deficit in HR children prior to reading instruction. In addition, a trend for lower rise time discrimination (RT) thresholds in HR children was also found. Further comparison provided evidence supporting the notion that pre-reading MA is a function of an individual's pre-reading PA.

Study 4 addressed questions concerning auditory temporal processing deficits in the early stages of reading acquisition based on a retrospective examination of the longitudinal data. Results indicated atypical performance of children who developed dyslexia in auditory processing of RT and PA at each of the three time points (kindergarten, first, and second grade). Additionally, results showed that RT and FM sensitivity in kindergarten uniquely contribute to growth in reading ability in grades one and two, even after controlling for letter knowledge and PA. Additional evidence was provided suggesting the possibility of a causal relationship where kindergarten RT significantly predicts later PA.

Study 5 focused on the association of MA growth with PA in early childhood development. Results demonstrated that children with dyslexia have MA deficits at all time points. Additionally, PA was found to contribute to MA development prior to the onset of formal reading instruction. After the start of formal reading instruction, decoding skills were found to be the major variable contributing to MA growth.

The final chapter summarizes the conclusions of this work, highlights its limitations and provides a critical discussion of its theoretical and practical relevance as well as suggestions for future research.

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Dyslexie is een neurologische aandoening die 5-7% van de populatie treft, gekenmerkt door ernstige en hardnekkige lees- en spellingproblemen, ondanks adequate intelligentie, onderwijs en remediëring. De heersende etiologische visie stelt dat dyslexie het gevolg is van een fonologisch tekort, meer bepaald in de kwaliteit en accuraatheid van fonologische representaties. Een essentiële component in de ontwikkeling van fonologische representaties is het bewustzijn van individuele spraakklanken (fonemen). Recente bevindingen suggereren het bestaan van een onderliggend tekort in basale auditieve temporele informatieverwerking bij personen met dyslexie. Deze theorie stelt dat een verstoring in het verwerken van snelle akoestische wisselingen in het spraaksignaal problemen veroorzaakt in de perceptie van gesproken taal, wat op zijn beurt leidt tot afwijkende foneemrepresentaties. Uiteindelijk verstoort dit het leren van foneem-grafeem koppelingen, wat zich vervolgens uit in lees- en spellingproblemen. Dergelijke enkelvoudige cognitieve deficitmodellen van dyslexie zijn echter niet in staat om alle gedragskenmerken van de dyslectische populatie te verklaren. Onderzoekers richten zich daarom op multifactoriële modellen, waarbij meerdere risico- en beschermende factoren probabilistisch op elkaar inwerken om het gamma gedragssymptomen bij personen met dyslexie te verklaren.

In deze studie werd nagegaan of kinderen en volwassenen met dyslexie problemen hebben met auditieve temporele informatieverwerking en wat de kenmerken zijn van deze tekorten. Daarnaast, binnen de context van multifactoriële cognitieve verklaringsmodellen, wilden we de aard en de rol onderzoeken van morfologisch bewustzijn (MB) als risico en/of beschermende factor voor de leesvaardigheden van kinderen en volwassenen met dyslexie. Om de effecten van MB en auditieve informatieverwerking op lezen en leesproblemen te evalueren, werden kinderen met familiaal risico (hoog risico groep – HR) en zonder familiaal risico op dyslexie (laag risico groep – LR) longitudinaal gevolgd doorheen hun vroege leesontwikkeling. We onderzochten dezelfde verbanden bij volwassenen met dyslexie.

In een eerste studie onderzochten we of auditieve verwerking, spraakperceptie, en fonologische vaardigheden bijdragen tot leesvaardigheid op volwassen leeftijd, onafhankelijk van of in samenspel met elkaar. De resultaten toonden dat fonologische tekorten en tekorten in auditief temporele informatieverwerking gerelateerd zijn aan leesvaardigheid. Echter, op individueel niveau kon het vooropgestelde cascade-effect van auditieve temporele informatieverwerkingsproblemen op het lezen niet teruggevonden worden. We voerden dan ook een tweede studie uit in dezelfde populatie om de compenserende rol van MB in de leesvaardigheid van volwassenen met dyslexie te onderzoeken. MB vormde een sterkere voorspeller voor woordlezen bij personen met dyslexie dan bij controlesubjecten. Hoewel volwassenen met dyslexie in het algemeen tekorten in MB vertoonden, werden er geen MB-verschillen gevonden tussen de groep van compenserende dyslectici en de controlegroep, wat impliceert dat MB daar intact was en dus mogelijkerwijze als compensatievaardigheid gebruikt kon worden.

De overige studies onderzochten de aard en ontwikkeling van auditieve temporele informatie-verwerkingsproblemen en MB bij jonge kinderen met dyslexie. Studie 3 onderzocht de relatie tussen fonologisch bewustzijn (FB), auditieve informatieverwerking en MB in de groep kinderen met HR en LR die nog niet leerden lezen. De resultaten toonden aan dat kinderen uit de HR groep een tekort hadden in MB voor ze leerden lezen. Daarnaast was er een trend van een lagere gevoeligheid voor *rise time* (RT) bij kinderen met HR. Verdere vergelijkingen ondersteunden dat MB functie is van het FB van het individu in de fase voor het kind leert lezen.

Studie 4 richtte zich op auditieve temporele informatieverwerkingsproblemen in de vroege stadia van het leren lezen, gebaseerd op retrospectief onderzoek van de longitudinale data. De resultaten wezen op een atypische prestatie in de auditieve verwerking van RT en FB bij kinderen die dyslexie ontwikkelden, dit op elk van de drie meetmomenten (kleuterleeftijd, eerste leerjaar, en tweede leerjaar). Daarnaast toonden de resultaten dat sensitiviteit voor RT en MB in de kleuterklas een unieke bijdrage leveren aan de toename in leesvaardigheid in het eerste en tweede leerjaar, zelfs na controle voor letterkennis en FB. Er werd aanvullend bewijs gevonden voor een mogelijke causale relatie tussen RT in de kleuterklas en FB op latere leeftijd.

Studie 5 focuste op de associatie tussen een toename in MB met FB in de vroege kindertijd. De resultaten toonden dat kinderen met dyslexie tekorten hebben in MB op elk meetmoment. Bovendien bleek FB bij te dragen aan de ontwikkeling van MB vóór de leeftijd waarop officiële leesinstructies gegeven werden. Na de start van leesinstructies bleken decodeervaardigheden de belangrijkste verklarende factor te zijn in toename in MB.

In het laatste hoofdstuk worden conclusies getrokken uit deze bevindingen en worden beperkingen van het onderzoek weergegeven. We geven een kritische discussie van de theoretische en praktische relevantie van deze resultaten, en eindigen met suggesties voor verder onderzoek.

Foreword

“Being held up by invisible men”

Although this verse has resonated with me for many years, it’s meaning has only become more real as I now reflect on my journey which has led me here.

The most appropriate place to start is with my first memory of reading and “Felix the Cat and his Magic Bag”. Felix the Cat was a book on my third grade classroom’s shelf with more pictures than words (most likely the motivating factor for me selecting it). I was to read Felix the Cat during the week and report back to the class all that I would have discovered in the text.

The memory of sitting on my couch and staring at those printed words is one of my most vivid memories as a child. Although the words were few, to me each one felt no less than an insurmountable barrier assembled form a random patchwork of letters on a page. I had been told that reading was a wonderful experience, an adventure, a joy, for it was a way of unlocking the secrets to a new world. I felt lied to, cheated in some way, for I found no joy in the experience, only frustration and disappointment that the mystery contained within “Felix the Cat’s Magic Bag” would remain hidden, and out of reach for me.

I could not read.

My struggle with reading and writing has been life-long. Regardless of the countless recesses spent writing lines of misspelt words, extra lessons or ‘special’ classes, my struggles persisted. I became a master at hiding my secret. In high school, I learned ways to conveniently avoid the embarrassment of reading publically as well as privately. Instead, I focused on math, science and art. I carefully selected classes in high school and university with the shortest reading lists and a lack of written papers. Just as Felix the Cat had remained unread, I graduated secondary school without knowing what it was like to have ever read a book.

--At this point in the story I feel I should note that the irony here has not eluded me. After a lifetime of meticulously avoiding reading and writing, I have committed the last four years of my life to reading and writing about reading and writing--

Now, as I near the completion of this dissertation, I have been told several times that I should be proud of ‘my completion’ of this dissertation and ‘my success’ in spite of being dyslexic. Those words have never sat comfortably with me, for ‘my completion’ and ‘my success’ are not and has never been mine alone. Since that week spent with “Felix the Cat” I have been fortunate enough to have been held up by a multitude of invisible men and women each contributing in their unique way to ‘my success’. These are the people who too often go unnoticed or who are forgotten. Yet as undeserving as I felt, they offered me an immeasurable amount of support which has culminated in allowing this body of work to become a reality. It is to these ‘invisible men’ that I dedicate this dissertation.

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CHAPTER 1

General Introduction

INTRODUCTION

As you look at these words your eyes will begin to track from left to right across the page while you almost effortlessly decode meaning from the collection of black marks and symbols on the page. This ability to encode and decode meaning and knowledge through a collection of specific markings, or simply put, to read and write, is an impressive feat. Unlike spoken language, which has resulted from biological evolutionary processes and can be mastered without the aid of direct instruction, learning to read and write is a recent human invention dating back nearly 5,000 years (Powell, 2009). As a result, individuals are not 'pre-wired' to read. Instead, the mastery of this complex task requires explicit instruction over a period of several years. Yet, as your eyes continue to fall upon these words and meaning is extracted, the complexity of the task is nearly taken for granted. For most adult readers the process has become so automated that word recognition occurs within the first 200 milliseconds of presentation, making it nearly impossible not to read (Yap & Van Der Leij, 1993). For most children the transition from an oral to a written language system is relatively effortless. However, for a small proportion of children, in the absence of any explanation, this task is nearly insurmountable. Such difficulties are often related to a developmental condition referred to as dyslexia (Snowling, 2000).

DYSLEXIA

Historically, the first recorded account of what we now describe as dyslexia was published in 1896 in the British Medical Journal by Dr. W. Pringle Morgan. In this early account dyslexia was conceptualized as being primarily a visual processing problem. This perspective prevailed until the mid 1900's when researchers began to build upon the work of Orton (1928) and expanded the view of reading disorders beyond that of mere visual processing. Over the ensuing decades the definition and diagnostic criteria of dyslexia have been thoroughly debated, a debate that has persisted until today.

The specific definitions of dyslexia have evolved to reflect the growing body of research and the shift in scientific understanding regarding learning disabilities. This evolution resulted in a move away from general descriptions of reading disorders to more specific types of reading problems.

Although an individual with dyslexia may present problems with various aspects of reading, such as the decoding of single words, fluency and/or comprehension, research has recognized that within the specific group of readers identified as dyslexics, comprehension issues are a result of a word reading bottleneck and not a primary deficit, as found in other groups of children. As such, recent definitions have been developed to reflect these insights. For instance, take the most frequently cited definition of dyslexia which has been developed by the International Dyslexia Association (IDA; Lyon, Shaywitz, & Shaywitz, 2003):

> *"Dyslexia is a specific learning disability that is neurological in origin. It is characterized by difficulties with accurate and/or fluent word recognition and by poor spelling and decoding abilities. These difficulties typically result from a deficit in the phonological component of language that is often unexpected in relation to other cognitive abilities and the provision of effective classroom instruction. Secondary consequences may include problems in reading comprehension and reduced reading experience that can impede the growth of vocabulary and background knowledge." (p. 2)*

Several key aspects of dyslexia may be extracted from this definition. First, the definition leads with a statement highlighting the neurobiological origins of the disability. This is important for two reasons. First, it reflects the current neuroimaging research which has demonstrated functional and structural differences in the brains of individuals with dyslexia versus typically developing readers (Richlan, Kronbichler, & Wimmer, 2013; Vandermosten, Boets, Wouters, & Ghesquière, 2012). Second, it acknowledges that for an individual to be considered dyslexic, their expressed reading problems may not be solely a consequence of external environmental factors. Research has shown that when compared with other poor readers of the same age, the word reading difficulties of individuals with dyslexia cannot be attributed to extraneous circumstances such as poor-quality teaching, sociocultural deprivation, home environment or low IQ (Snowling, 2000). Additionally, this definition stresses that dyslexia is a word-level problem and not centered at issues of comprehension, thus placing reading comprehension problems as a secondary issue (Fletcher, Lyon, Fuchs, & Barnes, 2006; Vellutino, Fletcher, Snowling, & Scanlon, 2004).

An aspect of this definition that may incite criticism is the assertion regarding the role of phonological processing in the definition. Although the majority of research has identified phonological impairments in individuals with dyslexia these deficits have not been found to be universal within the dyslexic population and, in turn, not all individuals with phonological impairments go on to develop the expressed behavioural attributes associated with dyslexia (Snowling, 2008). Yet the most prominent causal hypothesis associated with dyslexia centers upon the notion of a deficit within the phonological domain. Greater discussion regarding phonological impairments and the phonological deficit theory of dyslexia is provided later in this chapter.

Similar to the evolution of the definition of dyslexia, the diagnostic criteria used to classify individuals as being dyslexic have evolved over time to reflect the growing body of research. Historically, the central criterion used to identify individuals with dyslexia was a discrepancy between the degree of reading impairment and the level of intelligence the individual demonstrated (Snowling, 2000). This practice has recently been abandoned with the adoption of the response-to-intervention model (RTI). The RTI model includes the systematic application of evidence-based intervention strategies targeted to the individual's perceived deficit and then measures the individual's response to those interventions. Since dyslexia is seen as resistant to intervention and endures throughout life, RTI is thought to be an accurate means of assessing these characteristics, thereby ruling out deficits related to low socioeconomic conditions and poor instruction (Fletcher, Francis, Morris, & Lyon, 2005; Kavale, Kauffman, Bachmeier, & LeFever, 2008).

As definitions and diagnostic criteria have changed over time, so have the estimated prevalence rates of dyslexia. Typically, prevalence rates are estimated to be approximately 5 to 10 percent of the general population (Elliott & Grigorenko, 2014), yet in the past estimates have been as high as 17.4 percent in a school-aged population (Shaywitz, 2004). This variability in estimation is often a function of the, sometimes arbitrary, placement of the boundary between reading disability and what is considered to be a 'normal' reading population. Additionally, estimations have been found to vary with differences in the language of assessment and with the diagnostic tools and methods used.

Genetics and family history

Research over the past three decades has provided evidence of the substantial heritability of dyslexia. Although the exact genetic mechanisms and inheritance patterns still remain unknown, genetic research has identified several possible genes linked to dyslexia (Cardon et al., 1994; Pennington & Olson, 2005). Findings have noted that children were more likely to manifest reading problems in cases where the child had at least one dyslexic parent when compared with children from families where both parents were found to be typical readers (Elbro, Borstrøm, & Petersen, 1998; Lyytinen et al., 2006; Pennington & Lefly, 2001). In a review, Pennington and Olson (2005) noted that the influences of familiarity and heritability operate similarly across genders.

Theoretical Framework

Phonological deficit theory of dyslexia

Although poor reading and spelling are the most apparent symptoms of dyslexia, research has shown that the expression of dyslexia is not limited to these specific domains. Research has provided evidence suggesting that the poor decoding abilities of people with dyslexia stem from a cognitive deficit in the development of, or access to, phonological representations (Ramus & Szenkovits, 2008; Snowling, 2000; Tønnessen, 1997). Such observations have led to the development of the phonological deficit theory of dyslexia which postulates that the observed reading and writing difficulties of individuals with dyslexia are a function of a cognitive deficit in the ability to access, process and manipulate speech sounds (Snowling, 2000). Manifestations of this deficit have been observed in, and measured through, three aspects of phonological processing: phonological awareness (PA), verbal short-term memory (the part of our memory system that makes use of the so-called phonological loop), and lexical retrieval of the phonological representation of items (pictures, colors, digits and letters as measured by rapid automatic naming [RAN]) (Wagner & Torgesen, 1987). Yet, discussion persists surrounding the interdependence of these three phonological dimensions.

Within the context of an alphabetic writing system, learning to read requires the development of accurate grapheme-phoneme correspondences, requiring high quality phonemic awareness. Initial phonological representations represent large, global phonological characteristics of a word such as the syllable. Over time, and through explicit instruction, a child develops a more explicit awareness of the phoneme level of words. This gradual development of explicit phoneme representation is vital in the formation of accurate mappings of grapheme-phoneme correspondences (Goswami, 2002). The quality of such mappings have been shown to be crucially important and a strong predictor for later reading proficiency (Boets et al., 2011; Goswami, 2002).

According to the dual-route model of reading (Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001) initial reading is greatly reliant on the quality of an individual's grapheme-phoneme correspondences. The dual-route model of reading predicts that initial reading is performed through an indirect sub-lexical pathway wherein the written word is decoded through the dissection of the word into its principal component graphemes and corresponding speech sounds (i.e. phonological processing). As reading skills progress, a more direct and efficient lexical path is developed for higher frequency words. This lexical route utilizes a rapid visual recognition of a word resulting in the unlocking of the phonological code of the whole word, thus bypassing the slower grapheme to sound decoding of the sub-lexical route. In fluent adult readers both of these pathways are simultaneously activated during reading. The sub-lexical processes are relied upon to aid in the decoding of unfamiliar or pseudo-words while the lexical route remains the primary route for high frequency and irregular words (Coltheart et al., 2001). As a result, individuals with dyslexia are often found to perform poorly on tasks involving the reading of pseudo- or infrequent words.

Additional support for the phonological deficit theory of dyslexia has been provided through consistent findings of a pronounced deficit in the phonological skills of individuals with dyslexia regardless of age (Shaywitz et al., 2007) and language (Ziegler & Goswami, 2005). Research has also demonstrated the existence of a strong predictive relationship between these phonological processing skills and the development of reading (Boets et al., 2011; Mann & Liberman, 1984; Stanovich & Siegel, 1994). Furthermore, evidence of a possible causal role of the phonological deficit has been provided through several studies observing the presence of a phonological deficit prior to the onset of formal reading instruction and the relation of this deficit to later literacy achievement (Boets et al., 2011; Mann & Liberman, 1984; Pennington & Lefly, 2001; Wagner & Torgesen, 1987).

In relation to the exact nature of this observed phonological deficit underlying dyslexia, Ramus & Szenkovits (2008) noted that it still remains unclear whether the phonological representations are directly degraded, or whether there is a limitation in the ability to retrieve or store them in short- and long-term memory.

Auditory Temporal Processing Deficit Theory

A vital component in the development of phonological representations is the awareness of individual speech sounds. Findings from the past few decades have begun to suggest the existence of an underlying deficit in low-level auditory temporal processing within the dyslexic population (Boets, Wouters, Van Wieringen, & Ghesquière, 2006; Farmer & Klein, 1995; Habib, 2000; Tallal, 1980). Beginning with Tallal's 1980 study of the temporal order judgment of children with specific language impairments (SLI), research has explored the idea that the primary deficit of dyslexia could lay in deviant auditory processing skills.

Early research related the interpretation of 'temporal processing' strictly to rapid succession or short durational cues, as measured by gap-detection tasks (Tallal, 1980). However, recent studies have demonstrated that the deficits observed in dyslexic readers are not mainly linked to the processing of short, rapidly presented stimuli, but especially to the processing of dynamic slow rate acoustic features such as frequency modulation (FM) and sound rise time (RT) (Boets et al., 2006; Goswami et al., 2002).

This theory, termed the auditory temporal processing deficit theory, hypothesizes that a disruption in the way individuals with dyslexia process dynamic changes in frequency and amplitude of sounds can cause a cascade effect in speech perception, ultimately rendering the mapping of speech sounds onto corresponding symbols problematic, which, in turn, is manifested in reading and spelling problems (Bailey & Snowling, 2002; Tallal, 1980).

While not denying the phonological deficit theory of dyslexia, this theorized cascade effect originating from a deficit in individuals' ability to process speech-related acoustic cues, attempts to offer an explanation of the underlying deficit of the phonological impairment of an individual with dyslexia.

For instance, the identification of phonemes and syllables is dependent on changes in frequency and amplitude in the speech signal that occur in a time frame respectively between 50 ms (i.e. 20 Hz) to 500 ms (i.e. 2 Hz). Therefore, if individuals are affected by poor auditory processing of slow rate auditory cues (i.e., modulation rates between 2 Hz and 20 Hz), we would expect that the isolation or perception of syllables and phonemes in the speech signal would ultimately be effected. Such a disruption could impact the segmentation of the speech signal into smaller elements, thus hampering the development of syllable and phoneme representations and ultimately disrupting the creation of accurate mapping schemes between the speech sound and corresponding graphemes (Poelmans et al., 2011).

Poor auditory processing of slow rate auditory cues has not only been found in individuals with dyslexia (Lorenzi, Dumont, & Fullgrabe, 2000), but a relation between performance of slow rate modulation detection tasks and phonological abilities has been observed in both school aged and pre-reading children (Boets et al., 2011; Caroline Witton, Stein, Stoodley, Rosner, & Talcott, 2002; Witton et al., 1998).

Slow rate auditory modulations can be assessed by FM and RT tasks. FM detection assesses an individual's ability to detect fluctuations in a carrier frequency at a certain modulation rate. Studies on the FM detection of dyslexics and controls have found significant group differences, in which dyslexics have been shown to have a reduced sensitivity when compared to control groups, demonstrating the ability of FM tasks to differentiate between adult, school aged and pre-reading dyslexics from normal readers (Boets, Wouters, Van Wieringen, & Ghesquiere, 2007; Ramus et al., 2003; Caroline Witton et al., 2002; C Witton et al., 1998). Yet, in a review study by Hämäläinen et al. (2012), of the twelve papers examining FM perception, three of the studies were not able to replicate these group differences (Halliday & Bishop, 2006; Stoodley, Hill, Stein, & Bishop, 2006; White et al., 2006). In addition to the findings of group differences, a study by Witton et al., (1998) found that the phonological decoding skills of both dyslexics and controls significantly correlated with FM sensitivity of 2 and 40 Hz. Additionally, the review paper by Hämäläinen, Salminen, and Leppänen (2013) noted eight separate studies that reported correlations between FM detection thresholds and reading and/or spelling skills. Yet, three studies were unable to replicate these results (Dawes & Bishop, 2009; Heath, Bishop, Hogben, & Roach, 2006; Van Ingelghem et al., 2005).

Furthermore, RT, a measure of slow rate dynamic auditory processing, has been showed to be a sensitive measure in discriminating between populations of dyslexic and normal readers. RT discrimination tasks measure an individual's ability to detect subtle differences in the rate of change of an amplitude envelope. RT tasks allow for an indirect assessment of how well an individual can detect the onset of syllables which are necessary for speech perception (Goswami et al., 2002; Goswami et al., 2011; Poelmans et al., 2011). The perception of such cues are utilized in the segmentation of the speech signal into its base parts, such as syllables, and onset/rime (Goswami, Gerson, & Astruc, 2010). Significantly, detection of such cues have been shown to be associated with the reading, writing and phonological skills of adult and child populations (Hämäläinen, Leppänen, Torppa, Müller, & Lyytinen, 2005). Goswami et al. (2002) demonstrated that 25% of the unique variance in reading and spelling in children could be predicted by individual differences in RT sensitivity, when controlled for IQ and age. Findings demonstrating the relationship between RT and reading have also remained consistent across differing orthographies (Goswami, 2011). When comparing persons with dyslexia to typical readers, child studies have demonstrated consistent group differences in RT perception across various measurement techniques (for a review see Hämäläinen et al., 2013; note the exception of Hämäläinen et al., 2009). On the other hand, adult studies have not been so clear. Despite some studies showing significantly poorer performance on RT tasks in adults with dyslexia when compared with age matched controls (Corriveau, Pasquini, & Goswami, 2007; Hämäläinen et al., 2005; Thomson, Fryer, Maltby, & Goswami, 2006), findings vary depending upon the measurement techniques employed (see Pasquini et al., 2007 and Thomson et al., 2006).

Auditory temporal processing deficits have further been linked to biological differences of dyslexics and controls. Studies have shown anatomical myelination deficits in people with dyslexia. The degree of myelination in the brain has been related to the speed of nerve conduction velocity (Jack, Noble, & Tsien, 1975). It is thought that poor or disturbed myelination could have negative consequences for the accurate coding and transmission of rapidly changing sounds similar to those measured in the tasks described above (Vandermosten, Poelmans, Sunaert, Ghesquière, & Wouters, 2013).

It is worth noting that the auditory temporal processing deficit theory has drawn some criticism. Several studies have failed to replicate the reported auditory processing deficits in dyslexics (McArthur & Hogben, 2001) while other studies have suggested the observed auditory impairments are a maturation lag in auditory temporal processing (Hautus, Setchell, Waldie, & Kirk, 2003). Other arguments have criticized the lack of correlation between the magnitudes of the observed auditory processing level and phonological deficits (Ramus et al., 2003). Additional issues have also been raised concerning the consistency and universality of auditory processing deficits in dyslexic populations (Dawes & Bishop, 2009; Ramus et al., 2003).

Speech perception

The processing of speech requires the interpretation and recognition of high-level perceptual units such as words, and sentences. These perceptual units are an amalgam of various acoustic-phonetic cues that can be categorized into different timescales that correspond to phoneme (20Hz) and syllable (2Hz) presentation. Thus, for the auditory temporal processing theory to be accurate, a disruption in the speech perception of individuals with dyslexia should be measurable (Bailey & Snowling, 2002).

Past research has utilized various measures of speech perception, often under optimal listening conditions. Such conditions allow for the compensation of specific deficits in phoneme identification (Assmann & Summerfield, 2004; Manis et al., 1997; Ziegler, Pech Georgel, George, & Lorenzi, 2009). An alternative measurement, known as speech-in-noise perception, reduces such compensation by requiring a participant to identify and comprehend real speech sounds under varying noise-masking scenarios. Speech-in-noise tasks require an individual to separate the background noise from the target speech signal and produce precise representations of rapidly-evolving spectral information. Although speech-in-noise tasks are influenced by higher-order cognitive processes such as lexical and phono-tactic knowledge, they provide a more ecological and natural measure of speech sound processing than other speech tasks such as categorical perception. Although all listeners demonstrate some reduced capacity for perception under noisy background conditions, dyslexic children (Boets et al., 2011; Bradlow, Kraus, & Hayes, 2003; M. Snowling, Goulandris, Bowlby, & Howell, 1986; Wible, Nicol, & Kraus, 2002; Ziegler & Goswami, 2005) and dyslexic adults (Dole, Hoen, & Meunier, 2012) exhibit pronounced difficulty with this task while often not demonstrating any impairment of speech perception in silent conditions (Bradley & Bryant, 1983; Bradlow et al., 2003). It is worth noting, however, that (Hazan, Messaoud-

Galusi, Rosen, Nouwens, & Shakespeare, 2009) was not able to replicate these findings in an adult population.

Of the two studies which have assessed both of these measures of signal processing in the same population (Boets et al., 2011; Poelmans et al., 2011) only Boets et al. was able to demonstrate a clear relationship between a measure of auditory processing and speech perception. Boets and colleagues showed that children who went on to develop dyslexia were already impaired in slow-rate FM sensitivity and speech perception prior to reading instruction. These measures were also found to uniquely predict later growth in reading. Yet, a more recent study by Poelmans et al. (2011), which followed up the same population, showed that no clear evidence supporting a relationship between slow-rate dynamic auditory processing and speech perception existed in 6th grade children. The discrepancy between these findings could suggest that the link between auditory and speech perception skills disappears through development and may only be detectable in the pre-reading stage of development.

The Multiple Deficit Model

Of the two models previously discussed, both rely on a single cognitive deficit as the primary cause of the expressed literacy impairments that are characteristic of dyslexia. Although a single cognitive deficit model of dyslexia is attractive, it does possess some shortcomings. For instance, research has yet to produce evidence of a single cognitive deficit which is capable of explaining all of the expressed behavioural traits observed in a dyslexic population (Ramus & Ahissar, 2012). In addition, Pennington (2006) noted that no single deficit model of dyslexia is capable of explaining the higher than expected rates of comorbidity. For instance, dyslexia co-occurs at a greater proportion than expected by chance with other developmental disabilities such as ADHD, dyscalculia or specific language impairments (see Pennington, 2006 for a comprehensive overview). Under a single deficit paradigm, a distinct explanation for each co-occurring pair of disorders is required. In the case of the comorbidity between dyslexia and ADHD, Pennington (2006) noted a shared cognitive deficit in processing speed along with findings of separate cognitive deficits specific to each disorder, which contradicted the single cognitive deficit model.

Additionally, genetic studies have not been able to offer support for a single deficit model. As of yet, no single genetic study has been able to isolate a single gene determining dyslexia. Thus, researchers have concluded that the etiology of dyslexia is complex and involves many genes acting probabilistically, each offering small proportional contributions (Bishop, 2009).

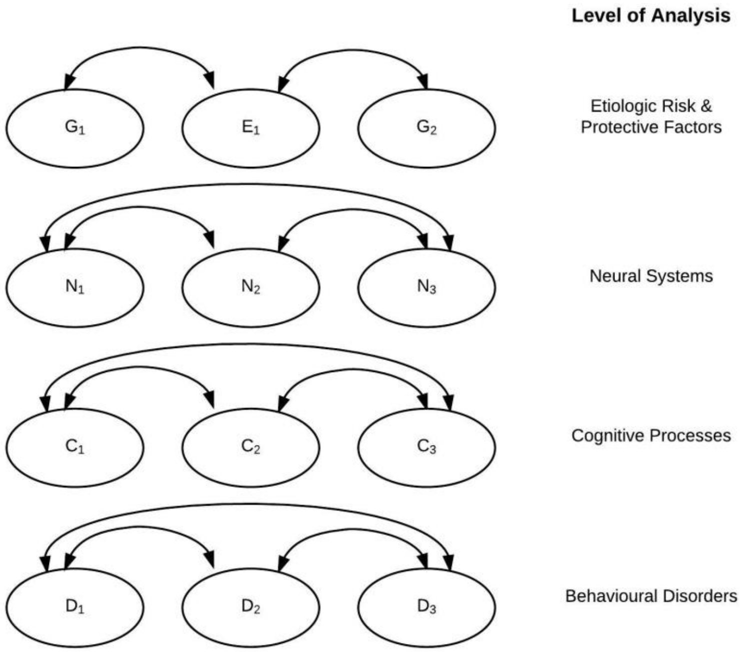

Figure 1: The Multiple deficit model as depicted by Pennington 2006.

In an effort to account for many of the shortcomings of a single deficit model of dyslexia, a multiple cognitive deficit model for understanding developmental disorders was proposed by Pennington (2006). The multiple cognitive deficit model, as depicted in Figure 1, illustrates a multifactorial etiology where multiple genetic or environmental factors act probabilistically as risk or protective factors. The interactions of these etiological factors result in the development of the specific cognitive risk or protective factors that increase or decrease the probability of the development of the expressed behavioural symptoms attributed to a specific developmental disability (Pennington, 2006). Therefore, when applied to the case of dyslexia, a single PA deficit would not be sufficient to produce the behaviour symptoms associated with dyslexia. Thus, there would need to be at least two deficits working in combination each adding incremental validity in predicting individual differences in the reading skills of an individual with dyslexia.

MORPHOLOGICAL KNOWLEDGE

As noted previously, research has begun to unravel the plausibility of a single deficit model of dyslexia. Although phonological processing deficits have been found to describe a significant portion of the variance in reading by individuals with dyslexia, a large proportion of the variance still remains unexplained. Coupled with the insights provided by Pennington's (2006) multiple deficit approach in explaining developmental disabilities, researchers have been led to explore alternative cognitive variables to account for the observed reading and spelling problems of persons with dyslexia. Here, we discuss morphological awareness (MA), a cognitive variable which is thought to work in conjunction with the phonological deficit and which, theoretically, has the potential to act as an risk and/or protective factor.

Morphology is the study of word formation by combining morphemes, the smallest linguistic units of meaning, to form more complex words. Within the English language two types of morphological structures can be identified: inflections and derivations. Inflections are morphological changes where the base word meaning is preserved. Such inflectional changes often include: person agreement, number and tense changes in the base word (i.e., jump, jumped, jumping). On the other hand, a derivation is the morphological change of a base morpheme by the addition of a prefix (i.e., dis-) or suffix (i.e., -er) usually resulting in a syntactic class change of the base word, for example the change of the verb 'jump' to the noun 'jumper'. Research has provided evidence that the correct use of inflectional morphemes and simple derived forms can be observed as early as kindergarten and first grade (Berko, 1958; Carlisle & Feldman, 1995)

When discussing the influence of morphology on reading processes, the term morphological knowledge is often used as a generalized umbrella term to describe both morphological awareness and morphological processing. Morphological awareness (MA) refers to an individual's *"conscious awareness of the morphemic structure of words and the ability to reflect on and manipulate that structure"* (Carlisle & Feldman, 1995, p. 194), while morphological processing refers to the unconscious use of a target word's morphological structure during language processing.

Morphological effects on early word processing have been observed in studies using priming paradigms with both derived and inflected words. These effects remain constant when controlled for orthography (Diependaele, Sandra, & Grainger, 2005; Giraudo & Grainger, 2001; Longtin, Segui, & Halle, 2003; Rastle, Davis, Marslen-Wilson, & Tyler, 2000; Rastle, Davis, & New, 2004) and semantic priming effects (Dominguez, De Vega, & Barber, 2004; Rastle et al., 2000; Raveh & Schiff, 2008).

Although neglected in previous studies of reading development and achievement, recent studies have begun to recognize morphology as a contributing variable in word recognition independent of orthographic processing, PA, rapid automatized naming, and vocabulary (Carlisle, 2000; Deacon & Kirby, 2004; Roman, Kirby, Parrila, Wade-Woolley, & Deacon, 2009), and in reading comprehension, after controlling for word reading, vocabulary, and PA (Carlisle, 2000; Deacon & Kirby, 2004; Nagy, Berninger, & Abbott, 2006; Tong, Deacon, Kirby, Cain, & Parrila, 2011).

Nagy and colleagues (2014) noted specific and separate means by which MA is capable of contributing to literacy outcomes. First, through ‘word form’, MA is capable of aiding in the identification, spelling and decoding of words. Due to the morphological structure of the English writing system, MA aids in the identification and pronunciation of a word form through the analyses and deconstruction of a word into its component morphemes. A review paper by Bowers, Kirby, and Deacon (2010) revealed how morphemic boundaries influence word reading by aiding in the pronunciation of letter sequences, in that, ‘ea’ is segmented and processed as one phoneme in the word ‘reach’ which composes a single morpheme, whereas ‘ea’ is pronounced separately in ‘react’ due to its placement in two adjacent morphemes. Furthermore, phonics alone cannot explain many of the linguistic inconsistencies in English, yet are sensible from a morphological perspective (Nunes, Bryant, & Bindman, 2006). For instance, we do not spell ‘*health’* as *‘helth’,* which would be consistent with phoneme-grapheme correspondence rules, but as ‘health’ in order to maintain the spelling of the root morpheme ‘*heal’*.

Lastly, morphemes retain syntactic and semantic information that is thought to aid in the comprehension of new or infrequent words. For instance, an understanding of the base morphemes ‘magic’ and ‘ian’ would help in facilitating in the comprehension of ‘magician’ as referring to a person who produces magic. The syntactic and semantic information provided by the morpheme has been demonstrated to aid in vocabulary acquisition (Nagy et al., 2006; Singson, Mahony, & Mann, 2000; Sparks & Deacon, 2015) and in the reading comprehension of children (Carlisle & Feldman, 1995; Deacon & Kirby, 2004) and adults (Nagy et al., 2006; Wilson-Fowler & Apel, 2015).

Yet the relationship between MA and reading may not be so straightforward. A recent study by Deacon, Benere, and Pasquarella (2013) has suggested that these two variables may share a bidirectional relation. Deacon and colleagues (2013) reported evidence supporting MA's influence on the growth of reading skills while additionally reporting a similar effect in the opposite direction, where children's early reading accuracy was associated with a growth in MA to the same extent as the previously mentioned direction. To further understand this potential bidirectional relationship, longitudinal research investigating the early development of MA prior to the onset of reading instruction is needed.

Morphological Awareness and Dyslexia

As past models and research of dyslexia have centered on deficits in phonological processing and awareness, morphological knowledge has been treated as a consequence of these deficits (Snowling 2000; Vallutino & Fletcher, 2005). Research across various ages and languages has shown that dyslexics underperform across a variety of measures assessing MA when compared with chronologically age-matched controls (Berthiaume & Daigle, 2014; Casalis, Colé, & Sopo, 2004; Fowler, Liberman, & Feldman, 1995; Shankweiler et al., 1995; Tsesmeli & Seymour, 2006). In studies employing a reading age match design, however, dyslexics were shown to perform similar to or better than younger, reading skill matched controls (Robertson, Joanisse, Desroches, & Terry, 2012; Tsesmeli & Seymour, 2006).

The fact that individuals with dyslexia perform poorer on MA measures compared to typical readers of the same age, but not relative to reading age matched controls, indicates that MA deficits are not causal to dyslexic's reading struggles. Thereby, it can be suggested that MA deficits are a consequence of the poor reading experience or of more primary deficits, such as those observed in the phonological representations of individuals with dyslexia.

In contrast, research of morphological processing has produced little evidence or agreement as to whether the ability to rapidly process written morphology is intact within individuals with dyslexia (Elbro & Arnbak, 1996, Quemart & Casalis, 2013 but see Deacon, Kirby & Parrila, 2006; Lazaro et al., 2013). It has been suggested that a hierarchical structure of linguistic units is employed during early visual word processing, in that the processing of smaller linguistic units (i.e, graphemes) are required to process larger-size units such as rhymes (Duncan, Seymour, & Hill, 1997). Such a situation would ultimately limit the visual processing of morphemes in a dyslexic population, thus limiting MP. Support of such a limitation was provided in a recent study of French speaking adolescents with dyslexia. Berthiaume & Daigle (2014) administered a judgment task to measure the reaction times of participants who were instructed to determine which of two visually presented pseudo-words most resembled a real word. Results of this study indicated some morphological sensitivity of the dyslexic participants, yet individuals with dyslexia were found to underperform when compared to both chronological and reading age matched controls. Contrary findings have been provided by Quemart and Casalis (2013) who in a masked priming experiment observed significant morphological priming effects in children with dyslexia, as well as in both chronological and reading age matched controls.

Nonetheless, several studies have proposed an alternative hypothesis wherein morphological knowledge is a relative strength and may offer a means of achieving some level of compensation for individuals with dyslexia (Burani et al., 2008; Elbro & Arnbak, 1996; Law, Wouters & Ghesquiere, 2015). Leikin and Zur Hagit (2006) have suggested that dyslexics may vary from normal readers in their use of the cognitive processes solicited while reading, and that dyslexics may rely on morphological decomposition during the process of initial visual word recognition. It is thought that, since dyslexics have impaired mapping schemes between graphemes and phonemes, they rely on lexical access through a morphological pathway early in life. Supporting this notion, Bryant et al. (1998) showed the existence of the relative strength of morphological processing in young dyslexic children. Although the relative strength of morphological knowledge is rarely found in age matched subjects, Casalis et al. (2004) found that dyslexics outperformed their reading age counterparts in morphological production tasks while performing equally well in a morphological sentence completion task. Casalis and colleagues concluded from these results that individuals with dyslexia might utilize the larger units of sound that are connected with meaning which comprise morphemes (for similar findings see Tsesmeli and Seymour (2006)).

As discussed in a review by Deacon and Tong (2016), the possibility of morphological knowledge aiding in compensation was predicted in a recent conceptualization of the dual-route model of reading (originally depicted in Coltheart et al., 2001). It is theorized that when dealing with novel or less automatized words dyslexics' phonological impairment limits their reliance on the sub-lexical route that involves decoding prior to lexical access. Thus, individuals with dyslexia are bound to utilize the lexical route, which has been argued to include not only direct lexical access but also indirect access through the aid of complex graphemes and morphemes (Grainger & Ziegler, 2011).

Support for this notion has been provided by research by Singson et al. (2000) and Nagy et al. (2006) that demonstrated the occurrence of a developmental shift with age, resulting in a greater reliance upon morphology as the role of PA decreases.

Additionally, Elbro and Arnbak (1996) presented two studies that provide evidence of the role of MA in compensation. In the first study, they found that dyslexic adolescents' reading speed benefited more from semantically transparent morphological structures than from matched control words. The improvement of response times was correlated with improvements in reading comprehension. These results differed from those of the matched control subjects who did not possess such a benefit. The second study presented by Elbro and Arnbak (1996) found that dyslexics were significantly better at reading texts which were deconstructed and presented as morphemes compared to texts presented as syllables, while reading level matched controls showed a trend in the opposite direction. Leikin and Zur Hagit (2006) also found that adult dyslexics benefited more from morphological priming than control readers did. They concluded that in the process of lexical access, compensated dyslexics may rely more on the slower morphological decomposition route than on orthographic or phonological codes to increase the speed of whole word recognition.

Yet, not all studies have been able to replicate this support. In a similar study involving Spanish speaking reading disabled children, Lázaro, Camacho, and Burani (2013) reported no advantage offered by morphemic structure to the disabled group compared with chronologically age and reading age-matched controls.

Furthermore, a study by Deacon, Parrila, and Kirby (2006) was not able to support morphological processing's role in compensation for adults with dyslexia, as dyslexics were not found to benefit form morphological facilitation during a lexical decision task. Deacon and colleagues concluded that normal reading adults possess sensitivity to the derivational structure of written words while high functioning dyslexics do not.

The current research project

Objectives

The general aims of this PhD project were twofold. First, within a context of the multiple cognitive deficit model of dyslexia, we wished to examine the nature of MA as a unique risk and/or protective factor relating to the literacy outcomes of children and adults with dyslexia.

A recent study by Cunningham and Carroll (2015) demonstrates an early relation between phonological processing (PP) and MA in which pre-reading PP was found to predict later MA in grade one students. Additionally, intervention studies have demonstrated gains in MA skills through PA instruction in both typically developing kindergarten children and those with speech impairments (Casalis & Colé, 2009; Kirk & Gillon, 2007). Yet, questions remain surrounding the continuity, over time, of the observable influence of PA on MA acquisition during the first years of reading. Therefore, we aimed to address questions concerning MA's and PA's interdependence pre- and post-reading. In addition, we attempted to assess the combined and independent contribution of each variable to the literacy achievement of children and adults with dyslexia. Furthermore, research has demonstrated that some individuals with dyslexia have been found to eventually achieve normal word reading levels in adulthood through some means of compensation. Our examination of this population will allow for the comparison of compensated vs. non-compensated dyslexics to evaluate the potential functioning of MA as a compensatory, or protective, factor within some adults with dyslexia.

The second aim of this project was to investigate the presence and nature of the temporal auditory deficit theory in dyslexia.

As the auditory temporal deficit theory incorporates the phonological deficit theory, various aspects associated with an individual's phonological representations were additionally examined to allow for an investigation of the whole spectrum of postulated deficits. Specifically, we administered a broad assessment battery examining various aspects of temporal auditory processing, speech perception, phonological ability and literacy skills. Such a broad testing battery permits the evaluation of the theorized cascade effect from the perception of specific auditory cues to speech perception, ultimately influencing phonological processing. As was noted earlier in this chapter, evidence supporting this postulated effect is scarce in the literature. In addition, evidence is still lacking as to which auditory temporal cues are most influential in this model.

Moreover, to evaluate any developmental and causal influence of either MA or auditory measures, we studied a population of pre-reading children with and without a family risk of dyslexia and followed them through the early stages of literacy development. Prior to this, we set out to examine the nature and expression of these relationships as represented within an adult population with dyslexia.

A general theoretical model of the variables examined within this project and their proposed interaction are represented in Figure 2.

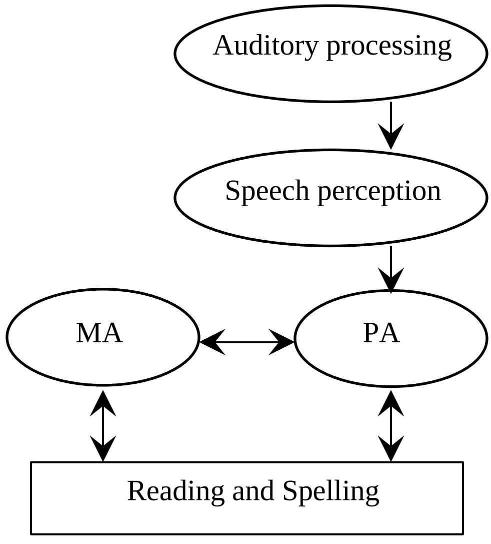

Figure 2. Overarching theoretical model pertaining to the current study

Participant Selection

To achieve our aims, child and adult populations were recruited. Recruitment procedures and a detailed description of each group are found below.

Study 1. The participants selected for this study initially included children ranging in age from 4 to 5 years old and attending Senior Kindergarten (SK) in the Ontario, Canada public school system. Half of the participants were classified as high risk (HR) for developing dyslexia, while the other half were considered as low risk (LR). Due to the tendency for dyslexia to run in families, the HR group was selected based upon the child having at least one first-degree family relative possessing an official diagnosis of dyslexia. The LR recruited population were matched to the HR sample group based upon measures of intelligence, socioeconomic status, gender, age and educational environment as control subjects.

The primary means of gaining participation were invitation letters distributed to families of Junior Kindergarten (JK) pupils a few months before entering SK. The letter explained the scope of the research and the basic requirements for participation. Distribution of the letters was facilitated by the schools and teaching staff. Letters were provided to each participating school and distributed to every student enrolled in JK during the months of May or June and once again when they enrolled as SK pupils in September. If the school or individual class maintained a class website, wiki or newsletter, we asked for a courtesy mention or an advertisement of our project placed on it. All means of advertising included reference and direction to a website (www.readingresearch.ca) specially created for this research project which provided more information as well as an alternate means of communication with parents. Parents who felt that they met the initial recruitment criteria were sent a parental informed consent form to be signed and returned to the researcher. Parents were also requested to complete a questionnaire accessed either online or received by post. The questionnaire investigated the general development, medical history and behaviour of the participating child along with evaluating the reading and spelling (dis)abilities of all members of the immediate family. Additionally, the questionnaire assessed the educational level and reading experience of each parent. The structure of this questionnaire was adapted from the Adult Reading History Questionnaire (Lefly & Pennington, 2000). Parental educational levels were classified on a seven point ISCED-scale

(International Standard Classification of Education by UNESCO, 1997). Potential existence of ADHD and behavioural problems were screened by the inclusion of questions taken from the Strengths and Difficulties Questionnaire (SDQ) (Goodman, 2001) and incorporated in the parental questionnaire.

HR children were selected for participation based on meeting set criteria: having at least one first degree family member possessing a formal diagnosis of a reading disability (i.e. dyslexia); possessing no signs of brain damage or long-term auditory or visual impairments; and being a native English speaker born in 2008 and entering SK.

Immediately following the HR student's recruitment, a LR population was recruited (following similar advertising efforts) from the class of the HR child. Prospective LR parents were asked to participate by the use of an identical questionnaire administered to the HR parents. By virtue of the questionnaire, pupils whose background variables, educational environment, measured IQ, gender and age best matched that of an HR pupil were selected for participation as an LR pupil.

*Study 2***.** Ninety university students were recruited for this study. All participants were at least eighteen years of age and were attending one of the three universities in Ontario, Canada. All participants were undergraduate students and native English speakers without a history of brain damage, language problems, psychiatric symptoms, visual problems or hearing loss.

Two populations of students were recruited, one having a previous diagnosis of dyslexia and the other having no documented history of reading problems. Recruitment of the dyslexic population for the study was made through the Special Needs office of Student Services, while the control population was gathered based on class announcements and posters placed throughout each campus.

Both groups of students were directed to www.jointhestudy.com where they could access more information regarding the study and researcher as well as register for or express interest in participating in the study.

OUTLINE OF DOCTORAL THESIS

The following five chapters of this doctoral thesis describe the results of the studies performed as well as a general discussion of the results. The chapters are organized based on the populations studied by first discussing the results of the adult population followed by the results of the longitudinal study involving pre-reading children.

Chapter 2 examines the temporal auditory deficit theory in an adult population of English-speaking university students. Skills relating to auditory temporal processing, speech perception and phonological skills along with measures of literacy achievement were assessed in 36 adults with a past diagnosis of dyslexia and 54 matched normal reading adults. Phonological skills were tested with a broad test battery including tasks of rapid automatic naming, verbal short-term memory and phonological awareness at various grain sizes. Dynamic auditory processing skills were assessed by means of a frequency modulation (FM) and an amplitude rise time discrimination (RT) tasks. An intensity discrimination task (ID) was included as a non-dynamic control task. Speech perception was assessed by means of sentences and words-in-noise tasks. Results from this study revealed a significantly poorer performance of the dyslexic group on auditory and phonological processing measures. Group differences were not found for speech perception. This study reports that phonological processing and not speech-in-noise processing mediates the relationship between performance on RT discrimination tasks and reading. Finally, inspection of the individual scores revealed that dyslexic readers showed an increased proportion of deviant subjects on the slow-dynamic auditory and phonological tasks, yet each individual dyslexic reader did not display clear patterns of deficiencies across the processing skills.

The results presented in this chapter support the hypothesis of phonological and slow-rate dynamic auditory deficits within a dyslexic population. These deficits were related to literacy, yet it is noted that at the individual level, problems in reading and writing cannot be explained by the cascading auditory theory. The chapter concludes by noting that dyslexic adults seem to vary considerably in the extent to which each of the auditory and phonological factors are expressed and interact with environmental and higher-order cognitive influences.

Chapter 3 focuses on MA within the same adult population as described in the previous chapter. Specifically, this chapter reports on the role of MA in literacy achievement and compensation in word reading of adults with dyslexia. Three questions are addressed: 1) Do adults with dyslexia demonstrate a deficit in MA and how is this potential deficit related to PA? 2) Does MA contribute independently to literacy skills equally in dyslexics and control readers? 3) Do MA and PA skills differ in compensated and non-compensated dyslexics?

The adults with dyslexia were found to perform significantly poorer on the MA tasks. Furthermore, the chapter describes two subgroups of the originally examined dyslexic group: a) those who possessed some level of compensation in their word reading and, b) a non-compensated group. Further analysis reported in this chapter noted that compensated dyslexics performed significantly better on morphological tasks than non-compensated dyslexics. Additionally, no statistical difference was observed in the performance on MA tasks between the normal reading controls and the compensated group (independently of PA and vocabulary). This chapter ends with a discussion of the results suggesting that intact and strong MA skills contribute to the achieved compensation of some adults with dyslexia. Implications for MA based intervention strategies for people with dyslexia are additionally discussed.

Chapter 4 is the first of three chapters that report on the child population of this PhD project. In a group of pre-reading children with a family risk of dyslexia and LR controls, the study sets out to answer questions concerning PA's relationship at various grain sizes (syllable, onset/rime and phoneme) with measures of auditory processing (FM and an amplitude RT task) and MA, independent of reading experience. Results of this study demonstrated an MA deficit in children with a family risk of dyslexia prior to reading instruction. In addition, a trend for lower RT thresholds of HR children was also found. Further, comparison of each measure with the noted PA deficits of the HR group revealed evidence supporting the notion of early pre-reading MA as a function of an individual's pre-reading PA.

Chapter 5 is the first of two chapters that retrospectively examine the longitudinal data of 43 pre-reading children with and without a family risk of dyslexia. Specifically, this chapter addresses questions concerning auditory temporal processing deficits in the early stages of reading acquisition. This longitudinal study of pre-reading children through literacy development attempts to clarify some issues pertaining to directionality within the theory. Results indicate atypical performance of children who developed dyslexia in auditory processing of RT and PA at each of the three time points (kindergarten, first, and second grade). Additionally, results show that RT and FM sensitivity in kindergarten uniquely contribute to growth in their reading ability in grades one and two, even after controlling for letter knowledge and PA. Highly significant concurrent and predictive correlations are reported even when controlled for autoregressive effects. These relations are discussed as potential evidence supporting a causal relationship between the auditory processing of RT and PA, with kindergarten RT significantly predicting later PA.

In *Chapter 6* we focus on MA progress in early childhood development. Using the same longitudinal data and population of children as reported in chapters 4 and 5, this chapter sets out to broaden our understanding of MA's growth and association with PA and early reading acquisition. Results of this study demonstrated that children who are later diagnosed with dyslexia possess MA deficits across all time points. Additionally, PA was found to contribute to MA development prior to the onset of formal reading instruction. Yet, after the onset of formal reading instruction, decoding skills were found to replace PA as the major contributing variable to MA growth. Findings in this chapter are discussed in terms of current theories of MA development and educational implications.

The concluding chapter, *Chapter 7*, of the thesis provides a critical discussion of the theoretical, and practical relevance of this PhD research project. In addition, it highlights some of the limitations of the research reported in this dissertation along with suggestions for future research.

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2 CHAPTER

The relationship of phonological ability, speech perception and auditory perception in adults with dyslexia[1]

This study investigated whether auditory, speech perception and phonological skills are tightly interrelated or independently contributing to reading. We assessed each of these three skills in 36 adults with a past diagnosis of dyslexia and 54 matched normal reading adults. Phonological skills were tested by the typical threefold tasks, i.e., rapid automatic naming, verbal short-term memory and phonological awareness. Dynamic auditory processing skills were assessed by means of a frequency modulation (FM) and an amplitude rise time (RT); an intensity discrimination task (ID) was included as a non-dynamic control task. Speech perception was assessed by means of sentences and words-in-noise tasks. Group analyses revealed significant group differences in auditory tasks (i.e., RT and ID) and in phonological processing measures, yet no differences were found for speech perception. In addition, performance on RT discrimination correlated with reading but this relation was mediated by phonological processing and not by speech-in-noise. Finally, inspection of the individual scores revealed that the dyslexic readers showed an increased proportion of deviant subjects on the slow-dynamic auditory and phonological tasks, yet each individual dyslexic reader does not display a clear pattern of deficiencies across the processing skills. Although our results support phonological and slow-rate dynamic auditory deficits which relate to literacy, they suggest that at the individual level, problems in reading and writing cannot be explained by the cascading auditory theory. Instead, dyslexic adults seem to vary considerably in the extent to which each of the auditory and phonological factors are expressed and interact with environmental and higher-order cognitive influences.

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INTRODUCTION

Dyslexia is a neurological condition affecting 5-7% of the population. This specific learning disability impacts an individual’s ability in learning to read and write despite adequate intelligence, education and remediation (Vellutino, Fletcher, Snowling, & Scanlon, 2004). It has been well established in the literature that the major causes of the expressed literacy problems lay within a deficit in the phonological domain, specifically in the quality and accuracy of phonological representations (Snowling, 2000). In this paper the auditory temporal processing deficit theory of dyslexia, and its cascading effects on speech and phonological processing will be examined. To this end, measures of slow-rate modulation, and speech perception will be assessed along with phonological and literacy measures in a population of university level dyslexic and non-dyslexic adult readers.

A vital part in the development of phonological representations is the awareness of how speech sounds correspond to a written symbol. Findings of the past few decades have begun to suggest the existence of an underlying deficit in low-level auditory temporal processing within the dyslexic population (Farmer & Klein, 1995; Habib, 2000; Boets, Wouters, van Wieringen, & Ghesquiere, 2006). Thus, if dyslexic readers perceive speech or related auditory cues inaccurately, the mapping of speech sounds onto their corresponding symbols will be problematic.

Beginning with Tallal’s 1980 study of temporal order judgment of children with specific language impairments, research has explored the idea that the primary deficit of dyslexics could lay in deviant auditory processing skills. Early research related the interpretation of ‘temporal processing’ restrictively to rapid succession or short durational cues (e.g., Tallal, 1980). However, recent studies have demonstrated that the deficits observed in dyslexic readers are not merely limited to the processing of short, rapidly presented stimuli, but also to slow-rate dynamic acoustic stimuli such as frequency modulations (FM) and sound rise time discrimination (RT). Such a deficit has been theorized to produce a cascade ultimately disrupting an individual’s reading and spelling abilities. If an individual were to be affected by poor auditory processing of slow-rate modulations (between 2 Hz and 20 Hz), it would be expected that speech perception would ultimately be affected, since the identification of phonemes and syllables depends on changes in the amplitude that occur respectively around 50 ms (i.e., 20 Hz) to 500 ms (i.e., 2 Hz). Such speech perception difficulties could impact the segmentation of aspects of the speech signal into smaller elements, thus hampering the development of phonological representations and ultimately disrupting the creation of accurate mapping schemes between speech sound and corresponding graphemes (Poelmans et al., 2011). Ultimately, these poor phoneme-grapheme representations will be expressed as poor coding and decoding abilities impacting word reading and spelling.

Slow-rate auditory modulations can be assessed by two different tasks, frequency modulation (FM) and rise time (RT) detection task. FM detection assesses the individual’s ability to detect frequency fluctuations in a carrier frequency at a certain modulation rate. Such frequency modulations could be said to represent the fine structure found within the envelopes of the speech waveform (Rosen 1992). Research on FM detection of dyslexics and controls have found significant group differences, where dyslexics have been shown to have a reduced sensitivity compared to controls, thus demonstrating FM task’s ability to differentiate between adult, school aged and pre-reading dyslexics from normal readers (Boets, Wouters, van Wieringen, & Ghesquiere, 2007; Ramus et al., 2003; Witton et al., 1998; Witton, Stein, Stoodley, Rosner, & Talcott, 2002). Yet, of the 12 papers examining FM perception in a review study by Hämäläinen, Salminen, & Leppanen (2012), three of the studies were not able to replicate these group differences (Halliday & Bishop, 2006; Stoodley, Hill, Stein, & Bishop, 2006; White et al., 2006).

In addition to findings of group differences, a study by Witton et al. (1998) found phonological decoding skills of both dyslexics and controls to be significantly correlated with FM sensitivity of 2 and 40 Hz. The review paper by Hämäläinen et al. (2012) noted 8 separate studies that reported correlations between FM detection thresholds and reading and/or spelling skills. Yet, 3 studies were unable to replicate these results (Dawes et al., 2009; Heath, Bishop, Hogben, & Roach, 2006; Van Ingelghem et al., 2005).

An alternative measure of auditory processing that taps into aspects of slow-rate dynamic processing mechanisms and that has been indicated to be a sensitive measure in discriminating between populations of dyslexic and normal readers is rise time discrimination (RT). Rise time, in comparison with FM tasks, measures the larger grain size of the speech waveform, which focuses specifically on the speech envelope (Rosen, 1992). Specifically, the RT task accesses an individual’s ability to detect subtle differences in the rate of change of an amplitude envelope. The perceptions of such cues are utilized in the segmentation of the speech signal into its base parts, such as syllables or onsets and rhymes, which is necessary for speech perception (Goswami, Gerson, & Astruc, 2010). Detection of such cues has been shown to be significantly associated with reading, writing and phonological skills in an adult population (Hämäläinen, Leppänen, Torppa, Muller, & Lyytinen, 2005). Goswami et al. (2002) demonstrated that 25% of unique variance in reading and spelling in children could be predicted by individual differences in rise time sensitivity, with IQ and age being controlled for. Findings demonstrating RT's relation to reading have also remained consistent across different orthographies (Goswami, Fosker, Huss, Mead, & Szucs, 2011). When comparing persons with dyslexia to typical readers, child studies have demonstrated consistent group differences in RT perception across various measurement techniques (for a review see Hämäläinen et al., 2012; note the exception of Hämäläinen et al., 2009). On the other hand, adult studies have not been so clear. Despite some adult studies showing significant poorer performance on RT tasks in adults with dyslexia (Corriveau, Pasquini, & Goswami, 2007; Hämäläinen et al., 2005; Thomson, Fryer, Maltby, & Goswami, 2006), findings vary between the different measurement techniques employed (see Pasquini et al., 2007 and Thomson et al., 2006). Traditionally, pure tone carrier signals are modulated in RT-tasks, but this lacks important frequencies of real speech. Hence, they do not activate a broader frequency region in the auditory system compared to speech weighted noise signals. In an effort to mimic the demand of real speech within the RT detection measure, Poelmans et al. (2011) utilized a single ramp rise time discrimination task that consists of a speech-weighted noise with a linear amplitude rise time. They showed that the application of a speech weighted noise signal resulted in reliable performance in children and did not produce any ceiling or floor effects, which differed from pilot studies of pure tone carrier signals.

However, not all auditory processing aspects seem to be impaired in dyslexic readers. In contrast to slow-rate dynamic auditory processing (RT, FM), intensity discrimination (ID) does not display group differences between typical and dyslexic readers (for a review see Hämäläinen 2012). This suggests that related task demands, attention and cognitive aspects are not the driving factor of the observed auditory problems since they are equal across RT, FM and ID tasks. In addition, as the RT measure includes changes of intensity over time, the lack of group differences on the ID tasks suggests that a poorer performance on the RT-task is not a reflection of difficulties in intensity discrimination ability but rather of the changes in intensity.

An understanding of slow-rate dynamic modulations such as RT and FM is important due to their prevalence in the speech signal, appearing at various grain sizes of phonological information ranging from intonation, onset and rhyme to the phoneme. If an individual has a deficit in processing these modulations, it is believed that it would be expressed in their ability to perceive speech.

Most often speech sound processing of dyslexics is assessed through the use of a categorical perception measure. Studies utilizing categorical perception tasks have demonstrated that subjects with dyslexia possess a reduced capacity for perception and categorization of phonemes (for a review see Vandermosten et al., 2011). However, results from such tasks are often restricted to a subset of the dyslexic population sampled (Adlard & Hazan, 1998; Manis et al., 1997) or to a specific speech condition or task (Blomert & Mitterer, 2004; Maassen, Groenen, Curl, Assman-Hulsmans, & Gabreëls, 2001). Typically, categorical perception tasks utilize optimal listening conditions. Such conditions allow for compensation of specific deficits in phoneme identification (Assman & Summerfield, 2004; Manis et al., 1997; Ziegler, Pech-Georgel, George, Lorenzi, 2009). Although speech-in-noise tasks are influenced by higher-order cognitive processes such as lexical and phonotactic knowledge, they provide a more ecological and natural measure of speech sound processing than categorical perception. By presenting speech stimuli in the presence of a masking noise, a participant's ability to identify and comprehend real speech sounds under varying noise-masking scenarios is assessed. The ability to identify speech-in-noise requires the individual to separate out the background noise from the target speech signal. This isolation allows for the individual to produce precise representations of the rapidly evolving spectral information. It has been shown that, although all listeners demonstrate some reduced capacity for perception under noisy background conditions, dyslexic children (Boets et al., 2011; Bradlow, Kraus, & Hayes, 2003; Snowling, Goulandris, Bowlby, & Howell, 1986; Wible, Nicol, & Kraus, 2002; Ziegler, Pech-Georgel, George, Alario, & Lorenzi, 2005; Ziegler et al., 2009) and dyslexic adults (Dole, Hoen, & Meunier, 2012) exhibit pronounced difficulty with this task while often not demonstrating any impairment of speech perception in silent conditions (Bradlow et al., 2003; Brady, Shankweiler &

Mann, 1983). Yet, Hazan, Messaoud-Galusi, Rosen, Nouwens, and Shakespeare (2009) were not able to replicate these findings in an adult population.

Although studies have demonstrated deficits independently in the slow-rate dynamic processing and speech-in-noise perception in individuals with dyslexia, only two studies have assessed both of these measures of signal processing in the same population (Boets et al., 2011; Poelmans et al., 2011). Boets et al. retrospectively explored this relationship in a population of preschool children who later developed dyslexia and showed that these children were already impaired in slow-rate FM sensitivity and speech perception prior to reading instruction. These pre-reading measures were also found to relate to each other and uniquely predicted later growth in reading. A more recent study by Poelmans et al. (2011), which followed up the same students of Boets, in 6th-grade children showed no clear evidence supporting relations between slow-rate dynamic auditory processing and speech perception itself. Given that this correlation was present at an earlier age (Boets et al., 2011), this might suggest that the link between auditory and speech perception skills is disappearing through development. However, more validation in adult participants is needed.

Although studies such as that of Boets and colleagues have found support for the auditory temporal processing deficit theory of dyslexia, the theory is not without its controversy. Criticism has arisen from the heterogeneity of the found deficits. It has been suggested that differences between group means are a reflection of a small number of poor performing dyslexic subjects. Ramus (2003) examined an adult population and noted that auditory deficits were limited to only 39% of the subjects with dyslexia and that auditory processing had only a weak correlation with phonology and reading. Other criticisms have suggested that general difficulties with task completion might underlie the poor performance of subjects with dyslexia in psychophysical studies and lead researchers to misinterpret non-sensory difficulties as sensory ones (Roach, Edwards, & Hogben, 2004; Stuart, McAnally, & Castles, 2001).

Our study will investigate the different levels of processing skills (i.e., auditory, speech-in-noise perception and phonological processing) in one and the same sample of dyslexic and normal reading adults. So far, such an integrative approach has not been applied to adults, despite being vital to understand the interrelations between auditory processing, speech perception, phonological processing and reading (problems). Furthermore, in contrast to previous studies, our study will not only investigate the interrelation between these skills and compare performance between groups, but we will also examine the individual level deviance scores.

Given that dyslexia is a disability measured and defined as deviant performance, research should reflect this by demonstrating a substantial number of individuals whose performance significantly differs from normal performance (Hazan et al., 2009, Heath et al., 2006; Ramus et al., 2003, Ziegler et al., 2008). As noted in Hazan et al. (2009) group comparisons could potentially mask significant individual differences or highlight differences which may not essentially be deviant, hence it is not sufficient in dyslexia research to merely demonstrate significant group differences without investigating the individual deviance scores. In addition, according to the auditory deficit theory, dyslexic readers should show consistent deficiencies across each level of processing; otherwise phonological impairments are presumably not secondary to speech and lower-level auditory problems.

Given that performance in adults is more prone to compensational mechanisms, the slow-rate dynamic tasks (FM and RT) will be assessed together with a control measure for attention and task complexity (ID). Although the inclusion of such well-matched control task helps in distinguishing effects of task demands from true effects, so far no study has included them as a control within all levels of statistical analyses. A few studies have included a control variable for attention and task related demands in group matching (Hämäläinen et al., 2005; Pasquini, Corriveau, & Goswami, 2007; Thomson et al., 2006), yet this does not prevent individual variation in groups exhibiting a significant role in relationships between psychophysical, phonological and literacy measures.

In sum, this study will address three main questions: (i) Do adults with dyslexia demonstrate deficits in auditory processing, speech perception and phonological abilities at the group level and at the individual level? (ii) Does a close relationship exist between the auditory processing, speech perception and phonological skills or do they rather contribute independently to reading skills? (iii) Based on individual deviance analyses, do the same participants display deviant scores across the three skills (i.e., auditory processing, speech perception and phonological processing)?

To achieve this, auditory processing skills will be assessed by two slow-rate modulation tasks, i.e., RT and FM, and by a control task, i.e., ID. Speech perception will be assessed by a word and sentences in noise task. Lastly, phonological processing will be accessed through the classical threefold of phonological awareness (PA), verbal short-term memory (VSTM) and rapid automatic naming (RAN) tasks.

MATERIALS AND METHODS

PARTICIPANTS

A total number of 90 undergraduate students were recruited for this study, 54 (36 female and 18 male) non-dyslexic and 36 (26 female and 10 male) participants with dyslexia. In order to participate, the dyslexic students needed to have a diagnosis completed by a registered and qualified clinical psychologist in secondary school or earlier and had to be registered at the office of Student Development & Services. The fact that the adults with dyslexia were selected from a university population, a higher level of reading achievement is expected than in a general sample of individuals of the same age, due to the selectivity of universities. This is reflected in some dyslexic student's normal reading and spelling scores as seen in Table 1. Based on their higher than expected literacy scores these participants may be considered as 'compensated' dyslexics. Research has shown that strengths in cognitive abilities, such as the use of contextual cues (Frith & Snowling, 1983; Nation & Snowling, 1998), semantic knowledge (Snowling, Bishop, & Stothard, 2000), visual memory (Campbell & Butterworth, 1985), and morphological knowledge (Elbro & Arnbak, 1996) help this group of individuals with dyslexia to minimize the expression of their reading difficulties.

The non-dyslexic population were comprised of students who have no documentation or history of reading difficulty and whose word reading scores did not fall in the bottom 5% of the WRAT norms (Wilkinson, 1993). Recruitment of the dyslexic population for the study was made through the University's Student Services, while the control population was gathered based on class announcements and posters placed throughout each campus.

All participants were at least 18 years of age and attended one of three universities in Ontario, Canada. All participants were native English speakers without a history of brain damage, language problems, psychiatric symptoms or visual problems which could not be corrected for by a corrective lens. Additionally all participants had adequate audiometric pure-tone hearing thresholds for the test ear (i.e., 25 dB HL or less on 0.25 - 8.0 kHz) and adequate nonverbal IQ defined by a standard score greater than 85 on Raven's advanced progressive matrices. Table 1 shows participant characteristics for the two groups. Groups did not differ in age, gender and nonverbal IQ.

Table 1: Participant characteristics

	NR		DYS			
Measure	*M*	*SD*	*M*	*SD*	*t*	*p*
Age (years)	22.0	3.0	21.8	4.8	0.227	1
Non-Verbal IQ	112.7	9.9	107.0	20.7	1.777	.158
Literacy						
Word-reading[a] (SS) (WRAT-III)	106.1	5.8	91.7	10.1	8.575	<.002
Spelling[a] (SS) (WRAT-III)	107.6	6.6	90.8	8.8	10.305	<.002
Literacy (*z*-score)	-0.1	1.1	-3.3	1.7	11.396	<.001

Notes. All *p* values are Bonferroni adjusted for multiple comparisons. Non-Verbal IQ = Raven advanced progressive matrices; WRAT-III = Wide Range Achievement Test III.
[a] Scores are standardized (M = 100, SD = 15). [b] Pearson Chi-Square value.

TASKS

Literacy

Literacy was assessed by the WRAT-III reading and spelling subtests (Wilkinson, 1993). The reading subtest required the subject to read aloud a list of 42 words. The subject received a single point for each correctly pronounced word to a maximum score of 42. The spelling subtest required the subject to accurately spell a series of dictated words. The words were presented orally by the test administrator preceding and following a sentence containing the target word. The test was scored by giving one point for each correctly spelled word to a maximum score of 40 points.

Phonological skills

Each domain of one's phonological skills, as represented in Wagner & Torgesen (1987), was individually tested.

Phonological awareness (PA) was assessed through the use of the Spoonerism subtest from the Phonological Assessment Battery (PhAB) (Frederickson, Firth, & Reason, 1997). Spoonerism tasks have been demonstrated to be able to significantly differentiate between an adult dyslexic population and control groups (Ramus et al., 2003). This test of PA targeted onset-rhyme awareness and requires phoneme manipulation and deletion. This task involved two parts. The first required the participant to replace the first sound of a word with a new sound (e.g., cot with a /g/ gives ‘got’). In part two, word pairs were orally presented to the participant; in turn they were requested to transpose the onset of the sounds of the two words. For example, “plane crash” will become “crane plash” or “King John” becomes “Jing Kon”. Rate scores, measured in number of correct items per second, were calculated as the total correct responses divided by the total time to complete the task. Due to ceiling level being reached within the control group accuracy was not separately evaluated.

Verbal short-term memory was assessed by The Number Repetition (digit span forward) subtest from The Clinical Evaluation of Language Fundamentals 4th edition (CELF-4) (Semel, Wiig, & Secord, 2003). Digit span forward required the immediate serial recall of an orally presented series of digits. List length was incrementally increased from two to nine digits and presented orally at a rate of one digit per second. The test score was calculated as the total number of correctly recalled lists with a maximum score of 16.

Verbal short-term memory was also assessed by the non-word recall subtest from the Working Memory Test Battery (WMTB) (Pickering & Gathercole, 2001). For this task sequences of single syllable nonsense words were presented orally to the participants. Each participant was requested to repeat the sequence in the correct order. The list length was incrementally increased, from one to six words in length. Six trials were available for presentation at each list length. The task was discontinued when three errors were made in a given list length. The test score was calculated as the total number of correctly recalled lists with a maximum score of 36.

Rapid Automatic Naming (RAN) was assessed through two naming tasks. A colour-naming test adapted from Boets et al. (2006) was selected. Five colours (black, yellow, red, green and blue) were presented in 5 rows containing 10 colour stimuli each. In addition, the object-naming subtest from The Phonological Assessment Battery (PhAB) (Frederickson et al., 1997) was used. Five line drawings of common objects (desk, ball, door, hat, box) were presented in 5 rows each containing 10 items. For both tasks participants were instructed to name aloud each of the objects or colours as quickly and as accurately as possible. A score of the number of symbols named per second was calculated.

Auditory processing and speech perception experimental setup

All tasks were conducted on campus and were administered individually in a private room, with minimal background noise and distraction. All auditory and speech perception tasks were performed on a Dell Latitude D510 and controlled by APEX software (Francart, van Wieringen, & Wouters, 2008; Laneau, Boets, Moonen, van Wieringen, & Wouters, 2005). Speech perception and auditory processing stimuli were presented through Sennheiser HDA 200 headphones to the right ear. Auditory processing procedure and tasks were adapted from those used and described by Poelmans et al. (2011).

Auditory processing tasks

All auditory processing task thresholds were estimated by means of a one-up, two-down adaptive staircase procedure which is designed to target a threshold corresponding to 70.7% correct responses (Levitt, 1971). Tasks were presented within a three-alternative forced-choice, ‘odd-one-out’ paradigm. In each trial three stimuli were presented requiring the participant to determine which sound differed from the others. An inter-stimulus interval of 350 ms was used. All tasks were terminated after ten reversals. Thresholds were the arithmetic mean of the last 4 reversals. Each participant completed two threshold runs of each task.

FM-detection task required participants to detect a 2 Hz sinusoidal frequency modulation of a 1 kHz carrier tone with varying modulation depth. The reference stimulus was a pure tone of 1 kHz. Modulation depth decreased by a factor of 1.2 from 100 Hz to 11 Hz. At this point modulation depth decreases by a step size of 1 Hz. The length of both the reference and the target stimulus was 1000 ms including 50 ms cosine-gated onset and offset. The detection threshold was defined as the minimum depth of frequency deviation (in Hz) required to detect the modulation.

Sound rise time discrimination sensitivity consisted of a speech weighted noise with linear amplitude rise times. Rise times varied logarithmically between 15 and 500 ms in 41 steps. The total duration of the stimulus was fixed to 800 ms, including a linear fall time of 75 ms. The stimulus of 15 ms rise time was used as the reference stimulus for each trial.

Discrimination thresholds were defined as the minimal difference in the rise time required discriminating between the reference and target stimulus.

Intensity discrimination task was identical to the FM and RT discrimination task in its presentation and procedure. Stimuli, of an 800 ms duration, consisting of a speech-weighted noise and a linear rise time and fall time of 75 ms were used. The stimulus of 70 dB SPL was utilized as a reference stimulus for each trial. Intensity was varied linearly between 70 dB SPL and 80 dB SPL in 40 steps of 0.25 dB SPL each. Discrimination thresholds were defined as the minimal intensity difference (in dB SPL) required to discriminate between the reference and the target stimulus.

Speech-in-noise perception

Speech-in-noise intelligibility was assessed for both words and sentences. During testing, the speech level was varied while the background noise level was fixed at 70 dB SPL. To assess the association of RT and FM discrimination in speech perception, two speech-in-noise tasks were administered. The first dealing with words-in-noise which would require less reliance on rise time processing and more on FM and the second which included sentences in noise which would rely more heavily on RT discrimination to accurately decompose and segment the sentence into finer grained elements for processing.

Words-in-noise perception was assessed with The Computer Aided Speech Perception Assessment (CASPA) developed by Boothroyd (2006) (for application see McCreery et al., 2010). A random selection of 3 lists of 10 CVC words were presented orally by a female speaker against a competing speech weighted noise at varying signal-to-noise ratios (SNR) (-5 dB, -10 dB and -13 dB). Each list contained a single occurrence of the same set of 30 phonemes (20 consonants and 10 vowels). A practice list of 0 dB SNR was first administered to the participant. Participants were instructed to repeat each target word after presentation; if the participant was unable to repeat the target word correctly they were instructed to repeat every perceived phoneme. The percentage of correctly perceived phonemes was calculated for each SNR. The Speech Reception Threshold (SRT) was calculated for each participant through fitting to the data a logistic function relating the percentage of correct responses to SNR level (for a similar approach see Poelmans et al., 2011).

Speech-in-noise intelligibility of sentences was assessed using stimuli adapted from The Hearing in Noise Test (HINT) (Nilsson, Soli, & Sullivan, 1994). Speech material consisted of English sentences spoken by a male speaker. The HINT stimuli consisted of a 70 dB long-term average speech spectrum masking noise and 12 equivalent 20-sentence lists. Two lists were administered after one practice list was presented. Lists were randomly selected from the 12 available. In the HINT adaptive procedure, beginning at 58 dB, the presentation level of all sentences were adjusted by 2 dB steps. Speech-in-noise intelligibility thresholds for each participant were calculated by averaging the last 6 SNR. Final values for each measure were inverted by multiplying by a factor of -1 to obtain a positive correlation matrix and for the creation of z-sores.

STATISTICAL ANALYSES

All data were checked with Shapiro-Wilk's test for normality. The assumption of homogeneity of variance was assessed by Levene's Test for Equality of Variances.

Individual deviance analyses of composite scores

A two-step process, as in Ramus et al. (2003) (also see Boets et al., 2006; Boets et al., 2007; Hazan et al., 2009; Reid, Szczerbinski, Iskierka-Kasperek, & Hansen, 2007), was used to create *z*-scores for each variable and to examine group differences in the proportion of deviant subjects on literacy tasks, phonological tasks, speech-in-noise perception and dynamic auditory perception. As done in Ramus et al. (2003) a control mean and standard deviation were calculated for each measured variable based on the scores of the normal reading sample. However, any subject of the NR sample scoring below the set threshold of -1.65 *SD* (bottom 5% of the population) was removed to compute the final control mean and *SD.* This extra step was a means to prevent any inattentive or distracted control from exaggerating the normal range of performance. *Z*-scores for all subjects were then recalculated based on this new final control mean and *SD*. Individual deviance was calculated from these *z*-scores and defined as any subject falling below the -1.65 *SD* threshold. For the purposes of this paper the term deviancy score is referring only to those scores falling below this threshold. We do not imply any answer to the delay/deficit discussion concerning dyslexia. In acknowledgment of the possible exaggeration of the dyslexics' deficits by such a two-step method, the more strict threshold of -1.65 *SD* was chosen.

The resulting *Z*-scores were used to create composite scores. For each participant a literacy score was calculated by averaging the *z*-scores of the WRAT reading and spelling subtests (Literacy); a phonological awareness (PA) score was calculated as the *z*-score of the Spoonerism task, The two RAN *z*-scores were averaged into one overall RAN score (RAN). Digit span and non-word recall tasks were averaged to create a verbal short-term memory score (VSTM). Due to the lack of strength in the correlations found within the auditory processing and within speech perception measures no composite scores were created for these groups of variables.

Multiple comparison corrections

In order to avoid the possibility of making a false positive conclusion in group comparisons all reported *p*-values for *t*-tests and ANOVAs were adjusted using a Bonferroni correction, which entailed the multiplication of the given *p*-value by the total number of comparisons per question to a maximum Bonferroni adjusted *p*-value of 1. If the adjusted *p*-value remains less than the original alpha of 0.05 then the null hypothesis was rejected.

RESULTS

PERFORMANCE OF DYSLEXIC VERSUS NORMAL READING ADULTS

Literacy

Literacy results are presented in Table 1. There was a statistically significant difference in the mean scores of reading and spelling between groups, with the dyslexic group preforming significantly poorer, $t(50.283) = 8.575$; $p < .005$, and $t(60.675) = 10.305$; $p < .005$

Phonological skills

Each domain of one’s phonological skills, as represented in Wagner & Torgesen (1987), was tested. Phonological awareness (PA) was tested by the spoonerism task of the PhAB, verbal short-term memory (VSTM) by digit span and non-word recall and RAN by object and colour naming. Test scores are presented in Table 2.

Table 2: Phonological abilities: descriptive statistics and *t* and *p*-values from independent *t*-tests

	NR		DYS			
Measure	M	SD	M	SD	t	*p*
Spoonerism (correct/sec)	0.23	0.08	0.10	0.04	9.042	<.005
Digit Span	12.32	1.87	10.78	2.00	3.712	<.005
Non-word recall	20.09	2.25	17.61	2.62	4.795	<.005
RAN (colour)	2.01	0.33	1.72	0.31	4.262	< 005
RAN (object)	1.77	0.24	1.50	0.25	5.059	<.005

Note. All *p* values are Bonferroni adjusted for multiple comparisons.

Independent sample *t*-tests were run to determine differences between groups in measures on phonological skills. Scores of the non-word recall and Spoonerism tasks were not found to be normally distributed. In order to approach a normal distribution they were transformed by a square root transformation. Adults with dyslexia were found to perform significantly poorer then controls on all measures.

Speech perception and auditory processing

In order to approach a normal distribution for more variables, the best score on the FM measure was transformed by a logarithmic transformation after the scores had been reversed, while the best score on the ID measure was transformed by the use of a square root transformation after the scores had been reversed, and the RT scores were transformed using a square root transformation (Field, 2009).

Since the aim of this research is to evaluate threshold estimations as an indicator of a subject's sensory capability, the two threshold trials were not averaged and instead the best score of each test was selected (for a similar approach see Boets et al., 2006). Threshold means and standard deviations of all auditory measures for each group can be found in Table 3.

Results demonstrated that dyslexic readers scored significantly poorer on measures of RT discrimination and ID, but not on FM-detection nor on the two tasks for speech-in-noise perception. Given the unexpected findings of a group difference in ID, ID was introduced as a control variable in order to determine whether a significant group difference on RT was due to general cognitive demands related to task design or intensity-related processes rather than dynamic-related processes. This confirmed the group difference for RT discrimination, $F(1, 87) = 9.492$, $p = .012$, partial η^2 = .098, while FM remained insignificant, $F(1, 87) = .643$, $p = 1$ (p values are Bonferroni adjusted for multiple comparisons).

Table 3: Auditory and Speech-in-noise Measures: descriptive statistics and *t* and *p*-values from independent *t*-tests

	NR		DYS			
Measure	M	SD	M	SD	*t*	*p*
FM (Hz)	3.82	1.38	4.58	2.38	-1.922	.174
RT (ms)	73.07	47.41	117.22	65.94	-3.695	.003
ID (dB)	1.04	0.54	1.46	0.76	-3.100	.009
HINT (SRT in dB)	-3.03	0.93	-3.11	0.91	-0.373	1
CASPA (SRT in dB)	-11.06	0.92	-11.01	1.02	0.243	1

Note. All *p* values are Bonferroni adjusted for multiple comparisons.

Relations between literacy, phonological and auditory skills

To assess the relations between subjects' literacy skills, phonological abilities and auditory processing skills, Pearson's correlation coefficients were calculated between the subjects' scores on measures of literacy, phonology, slow-rate dynamic auditory processing and speech-in-noise perception (lower left portion of Table 5). Phonological awareness was related to all measures of literacy, verbal short term memory and RAN, as well as RT and ID. Although FM was only found to relate to RT and ID, RT significantly correlated with measures of reading, spelling and measures of PA (spoonerisms and both RAN tasks).

Since the correlational analyses showed that reading and spelling correlate with both PA and RT, the independent contribution of each was assessed through a multiple regression analyses with both RT and PA for predicting reading and spelling (see Table 4). Analyses showed that RT offers no unique influence to both literacy measure above that offered through PA

The addition of ID in the model to control for attention mechanisms produced the same pattern of results for reading, $F(3, 85) = 21.512$, $p < .001$, $R^2 = .432$, and spelling, $F(3, 85) = 27.258$, $p < .001$, $R^2 = .490$, as well as the addition of age and IQ with ID, $F(5, 83) = 13.802$, $p < .001$, $R^2 = .454$, and $F(5, 83) = 17.591$, $p < .001$, $R^2 = .514$.

Table 4: Stepwise regressions showing the unique variance in the word reading, and spelling accounted for by PA and RT (R^2change and standardized Beta)

	Word reading		Spelling	
Step	R^2 change	β	R^2 change	β
1. PA	.412***	.935	.490***	.983
2. RT	.012	-.171	.000	-.030

**p* < .05. ***p* < .01. ****p* < .001.

Yet further investigation of RT's relationship with literacy within the dyslexic and the normal reading population did not reveal the same relationships present above. More specifically, the addition of group as a control measure to the regression model produced a larger significant contribution of PA, and none of RT, to reading, $F(6, 82) = 16.683$, $p < .001$, $R^2 = .550$ and spelling, $F(6, 82) = 23.392$, $p < .001$, $R^2 = .631$. In a similar vein, the other significant relationships that RT had across the entire population (lower left portion of Table 5) disappeared when controlling for group, with the exception of RAN object (upper right portion of Table 5).

Individual differences

The examination of performance at the individual level in both the NR and DYS group allows for a better understanding of the proportion of individuals within each group showing poor performance on each measured variable, even when group differences are not found. Such analyses will also allow determining if any individual subject had consistent deviant performance across all levels of processing, or whether deviant performance is a more random occurrence indicating the involvement of influences different from an auditory perceptual deficit (Heath et al., 2006).

Individual performance of the *z*-scores of RT, FM, ID, CASPA, HINT, PA, RAN, and VSTM were analyzed. A deviancy threshold of -1.65 was used. Thus, any z-score falling below this threshold would be considered as deviant performance as described by Ramus et al. (2003) and subsequently used by Boets et al. (2006), Boets et al. (2007), Hazan et al. (2009) and Reid et al. (2007).

The number and proportion of deviant subject per group on each of the variables are presented in Table 6. All measures, with the exception of

CASPA, HINT, ID and FM, demonstrated a significantly higher portion of deviant subjects in the DYS group when compared with the NR group.

Table 5: Correlations among measures for auditory processing, speech perception, phonology and literacy skills, with (upper part) and without (lower part) controlling for group

Measure	1	2	3	4	5	6	7	8	9	10	11	12
1. Spell	--	.366***	.093	.316**	.385***	.137	.207(*)	.065	.061	-.030	-.123	.033
2. Read	.675***	--	.227*	.239*	.323**	.055	.001	-.073	.146	.064	-.041	-.010
3. DS	.329***	.404***	--	.511***	.301**	.138	.191	.166	.150	-.128	.117	.147
4. NWR	.521**	.466***	.591***	--	.413***	.170	.194	.071	-.002	-.042	.106	.275*
5. PA	.700***	.642***	.457**	.582***	--	298**	.388***	-.075	.031	-.221*	-.028	.224*
6. RANob	.431***	.356**	.288**	.349**	.518***	--	.722***	-.255*	-.014	-.206	.018	-.042
7. RANcol	.430***	.280*	.314**	.346**	.542***	.775***	--	-.175	.081	-.281**	-.033	121
8. RT	-.220*	-.304**	.005	-.115	-.314**	-.382***	-.301**	--	.124	.135	-.108	-.183
9. FM	-.093	-.042	.057	-.101	-.132	-.109	-.015	.211*	--	.350**	-.023	-.033
10. ID	-.241*	-.173	-.229*	-.182	-.375***	-.321***	-.249*	.249*	.402***	--	-.047	-.196
11. HINT	-.112	-.057	.094	.076	-.047	-.003	-.046	-.085	-.015	-.032	--	.219*
12. CASPA	-.024	-.035	.119	.225*	.132	-.059	.090	-.165	-.043	-.181	.220*	--

Note. Read, WRAT reading; Spell, WRAT spelling; DS, Digit Span; NWR, non-word recall; PA, Spoonerism; RANob, RAN object naming; RANcol, RAN colour naming. **p* < .05. ***p* < .01. ****p* < .001. (*)Approaching significance of .05.

An evaluation of subjects with at least one score deviating more than 1.65 *SD* for the various auditory, speech and phonological measures, demonstrated that deficits appeared inconsistent, with some subjects deviating only on one task, while others on two or three tasks. Due to the observation of a high percentage of deviancy found on measures of RT (58%) and PA (72%) within the dyslexic group, an exploration of the interrelation between deficiencies in these different skills were made. ID was included to address any questions of influence of task related demands and/or attention. Figure 1 shows the calculated number of subjects showing isolated versus overlapping deficits. Results show that 28% of the dyslexic subjects possess a deficit in only PA (30% when controlled for ID), while 14% dyslexic subjects were found to only have a RT deficit (19% when controlled for ID). Dyslexic adults possessing an overlap in deficits were found to represent nearly half of the dyslexic subjects, 44% (37% when controlled for ID).

Table 6: Individual deviancy analysis for each variable

	DYS		NR			
Measure	n	%	n	%	χ^2	*p*
Literacy	31	86	0	0	70.932	< .001
PA	26	72	1	2	50.184	< .001
RAN	11	31	3	6	10.277	.001
VSTM	19	53	2	4	29.079	< .001
RT	21	58	12	22	12.129	< .001
FM	11	31	8	15	3.213	.073
ID	9	25	8	15	1.463	.227
HINT	1	3	1	2	0.085	.643
CASPA	5	14	9	17	0.127	.722

Note. Where cells have expected count less than 5, the Fisher's Exact test *p*-values are reported.

Although a large percentage of overlap is present, the proportion of shared PA and RT deficit does not exceed the expected proportions represented within the whole dyslexic group. Investigation of the normal reading individuals revealed no overlap between deviancy of RT and PA, yet this might be due to a low number of deviant subjects.

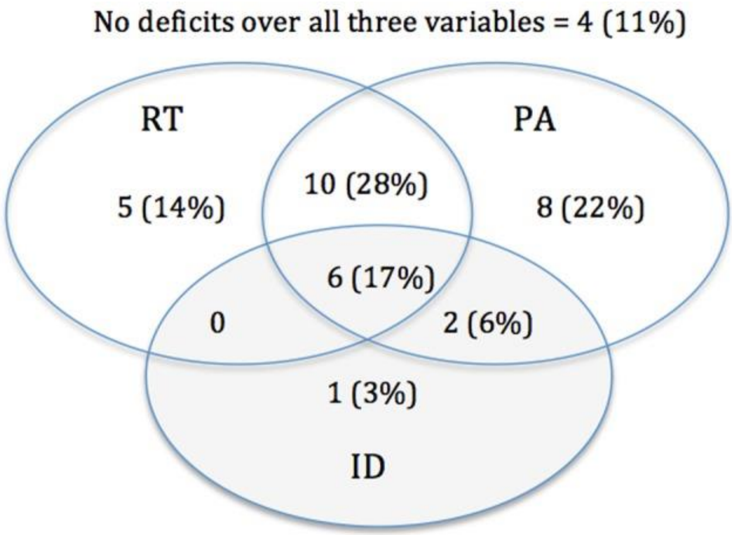

Figure 1. Distribution of RT, PA and ID deficits in the total sample of 36 dyslexic adult participants. Measured in absolute numbers and percentages of impaired subjects.

Discussion

It has been well established in the literature that dyslexic readers struggle with a phonological processing deficit and that such skills are related to literacy development and achievement (Snowling, 2000). Yet debate surrounds the question of whether this phonological processing impairment stems from a more primary deficit, such as a deficit in processing of speech sounds or due to a reduced sensitivity to slow–rate dynamic auditory information. This current study was set out to investigate speech perception and slow–rate dynamic auditory processing, in the form of RT and FM detection, in relation to phonological processing and literacy measures in dyslexic and normal reading adults.

Slow-rate auditory processing deficit

In line with the auditory temporal processing deficit theory of dyslexia, we had expected our auditory measures of RT and FM to differentiate between dyslexic and non-dyslexic students but not our non-temporal auditory ID task.

With regard to the slow-rate auditory processing tasks, group analyses revealed significant differences between adults with dyslexia and normal readers in RT while the uncorrected *p*-value was found to be approaching significance in FM. The lack of a significant group difference for the FM measure was unexpected, since the majority of studies in dyslexic adults have demonstrated clear group differences (Heath et al., 2006; Ramus et al., 2003; Witton et al., 1998; Witton et al., 2002). With regard to RT, our results are in line with the bulk of previous studies demonstrating a lower performance in dyslexic children (e.g., Fraser et al., 2010; Goswami et al., 2002; Poelmans et al., 2011) and adults (e.g., Hämäläinen et al., 2005; Pasquini et al., 2007; Thomson et al., 2006), suggesting a RT-deficit across development and languages.

Plausible hypotheses to explain the unexpected finding of not finding a group difference for FM in the presence of a RT-deficit may be (1) low sensitivity of the behavioural measures used, (2) the influence of task demands and attention difficulties, or (3) specific characteristics of the auditory stimuli being used.

Stoodley et al. (2006) suggested that in a population, such as the one included in this study, psychophysical measures may not be sensitive enough to detect subtle auditory processing impairments due to possible compensation. They found dyslexic adults to be unimpaired in psychophysical FM discrimination tasks, yet group differences were found when electrophysiological recordings were used. In doing so, Stoodley and colleagues demonstrated that the inability to detect low level auditory processing deficits in some groups of high functioning dyslexics can be attributed to the task sensitivity and the level of compensation achieved by the individual. The lack of group differences for FM discrimination for our adult population differed from behavioural studies in pre-schoolers (Boets et al., 2007) and children (Poelmans et al., 2011), which employed similar methodologies and stimuli. Yet findings on the RT measures were found to be significant, which would not have been expected if Stoodley's theory of compensation influences is consistent across all psychophysical tasks, unless RT tasks offer greater sensitivity.

Criticism regarding the influence of task demand and complexity of psychophysical tasks (see Roach et al., 2004) could explain the inconsistency of these results and the unexpected group differences on the ID task. Of the 16 studies reviewed by Hämäläinen et al. (2012) that included a measure of ID, only two found a significant group difference between individuals with dyslexia and normal readers. In the only adult study which found a group difference in ID (Thomson et al., 2006), the authors attributed their findings to the task difficulty of their ID measure. Such findings of unexpected differences may support Roach's et al. (2004) claim that poor performance and findings of group differences on psychophysical tasks are likely to be a function of attention and general task performance. In order to control for such task demand differences, ID was included in the statistical analyses as a control measure for all levels of analyses. After controlling for ID, group differences on RT remained present, indicating that this difference is rooted in processing stimuli-related properties differently rather than in attention differences.

Since our results do not clearly support the two explanations above, it is more likely that the pattern of results can be explained by a very specific deficit in slow-rate dynamic auditory processing. FM and RT tasks differ in how the auditory information is represented in the speech signal. As discussed by Rosen (1992), FM represents the fine structure of the speech waveform, while RT represents amplitude aspects of the speech envelope. The distinct pattern of results between RT and FM suggests that in adult dyslexics, the primary auditory dysfunction is more likely to be found in the perception of slow-rate dynamic auditory cues related to the speech envelope, as measured by RT, and not in the fine-structure, as measured by FM. Such findings reinforce previous studies in both child and adult populations (Fraser et al., 2010; Goswami et al., 2002; Poelmans et al., 2011; Thomson et al., 2006).

In sum, our results do not support a general deficit in slow-rate auditory processing of adult with dyslexia, yet, a subgroup of the adult dyslexic population may possess a more specific slow-rate dynamic processing deficit specific to the envelopes of the speech waveform.

Speech-in-noise perception deficit in individuals with dyslexia

Slow-rate dynamic auditory cues are found in abundance in speech. It is believed that a deficit in the processing of these auditory cues, such as RT and FM, would ultimately lead to a disruption in speech perception.

Unlike the results of auditory processing, this present study was not able to demonstrate any evidence to support the continuation of the speech-processing deficit observed in youth (Boets et al., 2007; Bradlow et al., 2003; Snowling et al., 1986; Wible et al., 2002; Ziegler et al., 2005; Ziegler et al., 2009) into adulthood, suggesting developmental or task related influences. Although our speech masking stimuli were in line with previous studies with children, it may not have offered sufficient difficulty for use in an adult or a highly compensated population (Pennington, Van Orden, Smith, Green, & Haith, 1990). According to a recently published study by Dole (2012), a stationary speech weighted background noise, as used in the present study, is less effective in differentiating between dyslexic and normal reading adults than modulated noises and background speech masks. Under the masking conditions of background speech or modulated noise an individual must rely on temporal dips in the masking noise to extract signals of the target speech signal (Howard-Jones & Rosen, 1993). It is thought that individuals with dyslexia may have difficulty perceiving these temporal dips, which is in line with our results of a RT deficit. Future studies should take into account Dole's findings to further assess the potential cascade of the RT difficulties observed in some dyslexics.

Slow-rate auditory processing and speech perception relationship

Our findings showed significantly poorer performance in adult dyslexic readers on the RT task assessing slow-rate dynamic auditory processing, which relates to amplitude aspects of the speech envelope. If an indirect path of an RT deficit through speech perception existed, we would have expected to find a correlation with the sentence in noise measure that required a greater reliance on larger grain segmentation of the sentence stimuli. However, examination of the relationships between these variables could not clearly support this hypothesis. Yet, once controlled for group, CASPA was found to relate to phonological skills.

As discussed earlier, the use of stationary noise in our speech perception tasks may have limited our ability to find relationships with RT, which might be more closely related to speech perception in modulated noise. An alternative interpretation is that slow-rate auditory processing independently relates to reading related measures and not via speech perception measures. However, such a situation remains unlikely considering the prevalence of slow-rate dynamic auditory cues in the speech signal. Therefore one would expect to find a relationship between these two variables. Finally, Poelmans et al. (2011) offered an alternative explanation, stating that the lack of relationship could be a consequence of the fact that the developmental link between these variables diminishes over time and is no longer evident in later years.

Due to the lack of evidence found to support the relationship of auditory deficits and speech perception in adults, our results do not support the theoretical cascade effect of the auditory deficit through speech perception to one's phonological representations.

Slow-rate dynamic auditory processing, PP and literacy

No significant correlations were found with FM nor with speech perception tasks. On the other hand, RT was found to correlate with measures of reading, spelling, phonological awareness and RAN, similar to findings of Thomson et al. (2006). Taking the regression analyses into account, it appears that any relationship between RT and reading is mediated through phonological processing and not speech-in-noise. These findings were similar to that of Pasquini et al. (2007). As discussed by Hämäläinen et al. (2005) it is highly improbable that the lower level skills of RT discrimination could be influenced by an individual's poor phonological awareness. Therefore, it is reasonable to assume that either this relationship reflects the same underlying perceptual deficit, or the ability to detect rapid changes in the speech envelope has a causal role in the development of PA. Although once controlled for group these relationships could no longer be supported, indicating that RT is not a good predictor of reading abilities in dyslexic or in normal readers. Yet, it is worth noting that a different pattern of findings might have emerged if a more direct assessment of decoding was employed, such as non-word reading measure (Hämäläinen et al., 2005).

Although the correlational analyses across all participants suggest interrelations between PA and RT, this finding should be nuanced at the individual level. When the prevalence and overlap of deviant performance on PA and RT was evaluated at the individual level, nearly half (45%) of the dyslexic population was found to possess a deficit in both, while 28% and 14% of the dyslexic population was found to have an isolated deficit in PA or RT, respectively (30% and 19% when controlled for ID). Despite co-occurrence in a large subsample of dyslexics, independence is suggested because the overlap between these variables is in proportion to what would be expected based on the frequency of each deficit in the total dyslexic group (i.e., 72% for a PA-deficit and 53% for a RT-deficit). Complemented with the lack of relationships once group was controlled for, it appears that phonological deficits seem not to be necessarily secondary to auditory problems since both deficits do not co-occur in every dyslexic subject. To increase our understanding, a longitudinal pre-reading study will be needed to assess the prevalence of the double deficit in RT and PA at earlier stages of reading development. In addition, training studies could help in verifying how one skill influences the other.

Given that in our adult study a large proportion of reading (problems) still remains unexplained, a multifactorial approach should be explored to fully identify the mechanisms underlying dyslexia. By investigating alternative cognitive factors, such as orthographic or morphological processing (Bekebrede, van der Leij, & Share, 2007), perceptual factors (Stein, 2001) and biological explanations (Nicolson, Fawcett, & Dean, 2001), the variance and comorbid symptoms associated with the dyslexic population can be better understood.

Limitations and implications

A limitation of this study was the sole inclusion of university students with dyslexia. It is reasonable to assume that by mere virtue of the fact that these young adults have reached university level education, varying levels of compensation are present in this specific group. Research has shown that the presence of relatively stronger cognitive abilities in some children with dyslexia allows for the minimization of parts of their phonological deficit later in life, allowing for the attainment of normal reading ability (Shaywitz et al., 2003). For example, a reliance or a strength in the use of contextual cues (Frith & Snowling, 1983; Nation & Snowling, 1998), semantic knowledge (Snowling et al., 2000), visual memory (Campbell & Butterworth, 1985), and morphological knowledge (Elbro & Arnbak, 1996) had been shown to aid in a dyslexic's ability to minimize the impact of the deficit in the expressed reading abilities. Stoodley et al. (2006) had also noted similar top down compensation processes influencing results of slow-rate dynamic auditory processing tasks (for a description of possible top down compensation processes see Pichora-Fuller, 2008). Therefore, percentages of observed deviant performance on slow-rate dynamic auditory processing tasks and phonological awareness measures could be underrepresented within our sample. Such potential levels of compensation limit our ability to extrapolate any findings to the general adult dyslexic population and could have potentially limited our ability in establishing clear group differences or correlations between variables. Having said this, our results do have implications in typifying the characteristics of dyslexic adults in higher education and broadening our understanding of how compensation may be expressed. This is especially relevant since accommodations are offered based on valid diagnosis given to them. Although the RT task sensitivity is lower than the phonological tasks' sensitivity, our result did demonstrate its potential to be included as an additional screening measure, for it was able to characterize a proportion of dyslexic adults not identified by a PA measure alone. Our data showed that purely relying on a PA tasks will result in missing a small subsample of dyslexics (in our study 14%).

A second implication is that a control task should be included. Our findings show the possible overestimation of the number of dyslexics when attention and task related demands are not accounted for. To avoid overestimation, future research should apply such a control task as presented in this paper, when designing a psychophysical testing battery and screening tools. Therefore, future development and study of this measure is still needed.

CONCLUSION

In summary, our results suggest that the lower sensitivity to RT cues that was observed in dyslexic children is still observable in adulthood, while FM deficits are not. Hence, our results suggest that a general slow-rate dynamic auditory processing deficit may not be present within an adult dyslexic population, but may be confined to speech envelope cues rather than to fine structure. RT's influence on literacy outcomes was not direct and was found to be mediated through phonological processing (this relationship was lost once controlled for group). Unlike studies in younger children (Boets et al., 2006), the existence of speech-in-noise perception deficits and its mediating role in auditory processing and reading-related measures was not observed. Further research is needed in this area with attention to the selection of speech-in-noise masking stimuli and the sampling of a more diverse adult population, which does not primarily contain a university sample.

Although findings of a deficit in RT and its correlation with phonological skills are significant when examined across the entire population, many dyslexic subjects with a severe deficit in one of these skills were often found unimpaired in the other skills. At best, conclusions regarding the primary deficit of dyslexia being a slow-rate dynamic auditory processing deficit should be restricted to the processing of RT cues and can only be generalized to a subgroup of adults with dyslexia. Such a lack of consistency could implicate the necessity of a multifactorial model of dyslexia.

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CHAPTER 3

Morphological Awareness and its Role in Compensation in Adults with Dyslexia[2]

This study examines the role of morphological awareness (MA) in literacy achievement and compensation in word reading of adults with dyslexia through an exploration of three questions: 1) Do adult dyslexics demonstrate a deficit in MA and how is this potential deficit related to phonological awareness (PA)? 2) Does MA contribute independently to literacy skills equally in dyslexics and control readers? 3) Do MA and PA skills differ in compensated and non-compensated dyslexics?

A group of dyslexic and normal reading university students matched for age, education and IQ participated in this study. Group analysis demonstrated an MA deficit in dyslexics; as well, MA was found to significantly predict a greater proportion of word reading and spelling within the dyslexic group compared to the controls. Compensated dyslexics were also found to perform significantly better on the morphological task than non-compensated dyslexics. Additionally, no statistical difference was observed in MA between the normal reading controls and the compensated group (independent of phonological awareness and vocabulary).

Results suggest that intact and strong morphological awareness skills contribute to the achieved compensation of this group of adults with dyslexia. Implications for MA based intervention strategies for people with dyslexia are discussed.

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INTRODUCTION

Dyslexia is often characterized as a difficulty with the development of effective word-decoding strategies, low levels of word reading and poor spelling performance (Vellutino, Fletcher, Snowling, & Scanlon, 2004). Research has demonstrated that individuals with dyslexia often have poor phonological representations and deviant phonological processing skills (Snowling, 2000). Although this is the accepted view, recent studies have suggested that phonological representations of dyslexic individuals may be intact indicating a deficit in the access to these representations or in phonological skills (Ramus et al., 2013). Evidence of a phonological deficit has been provided by several studies demonstrating dyslexics' poorer performances on measures assessing phonological short term memory, phonemic and phonological awareness, and rapid lexical access when compared to their reading age matched peers (for a review see Snowling, 2000).

The importance of these skills is represented in the Dual Route Model of reading (Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001), characterizing the two paths to achieve lexical access while reading: the lexical route and the sub-lexical route. Unlike the lexical route, the sub-lexical route is reliant on an individual's phonological processing ability. The sub-lexical route requires the decomposition of a word into its base components before seamlessly blending associated grapheme–phoneme correspondences allowing an individual to decode new or unfamiliar texts. Such ability is crucial in the independent learning of new words and the reading of unfamiliar texts, which affects word reading, comprehension and vocabulary acquisition. According to the phonological representation hypothesis, acquisition of these grapheme-phoneme correspondence rules are difficult for dyslexic readers due to the poor representation of phonemes and lexical memory (Elbro, 1996; Swan & Goswami, 1997). Such phonological deficits have been observed to characterize adults with dyslexia (Vellutino et al., 2004). Findings have indicated that phonological awareness does not develop in accordance with chronological age or reading level (Bruck, 1993; Miller-Shaul, 2005), therefore, deficits in this area persist into adulthood. This being said, some adults with dyslexia are able to compensate for their deficit and minimize its impact on reading. It is believed that these compensated dyslexics achieve word reading success through the application of various top down and/or bottom up strategies allowing them to bypass their poorly developed phonological skills. Research has shown that strengths in cognitive abilities, such as the use of contextual cues (Nation & Snowling, 1998), semantic knowledge (Snowling, 2001), visual memory (Campbell & Butterworth, 1985), and morphological knowledge (Elbro & Arnbak, 1996) help individuals with dyslexia to minimize the expression of their reading difficulties.

Due to the nature of the English language, words are formed by morphological and phonological elements (Chomsky & Halle 1968). It can be assumed that an explicit knowledge of both language elements would aid in the decoding process and in visual word recognition (Rastle, Davis, Marslen-Wilson, & Tyler, 2000). Morphemes, the smallest linguistic units of meaning, are used in combination to form more complex words. Within the English language, two types of morphological processes can be identified: inflectional and derivational. Inflections are morphological changes often altering the grammatical function of the word where the base word's meaning is preserved. Such inflectional changes result in person agreement, number and tense changes in the base word (e.g., jump, jumped, jumping). On the other hand, a derivation is a morphological change of a base morpheme through the addition of a prefix (e.g., dis-) or suffix (e.g., –er) usually resulting in the generation of new words which differ from the base word in meaning and possibly word class (Kirby et al., 2011); such can be seen in the change of the verb 'jump' to the noun 'jumper'.

Knowledge of the morphological principles of the English language aids in the reading and understanding of many of the language's linguistic inconsistencies. For example, the word *health* is not spelled as *helth*, which would be consistent with phoneme-grapheme rules, yet it is written in a way to preserve the spelling of the root morpheme *heal*. Research has shown that the conscious ability to reflect on and manipulate the morphemic structure of words – also known as morphological awareness (Carlisle, 1995) – has been found to contribute to reading outcomes and development independently of phonological awareness (for a review see Bowers, Kirby, & Deacon, 2010; Mahony, Singson, & Mann, 2000; Nagy, Berninger, & Abbott, 2006). Research has provided evidence that morphological awareness can be observed as early as kindergarten and first grade (Berko, 1958; Carlisle, 1995). Unlike phonemic awareness, regression analysis has demonstrated morphological awareness' contribution in predicting word reading ability increases through time (Carlisle, 1995; Singson, Mahony, & Mann, 2000). These results, however, could not be replicated by Roman, Kirby, Parrila, Wade-Woolley, and Deacon (2009). Instead Roman et al. found a constant influence of both variables in children in grades 4, 6 and 8.

Morphological awareness' importance in reading has contributed to its role in decoding skills, word recognition, comprehension and motivation (Carlisle, 1995; Carlisle, Colé, & Sopo, 2004; Deacon & Kirby, 2004; Roman et al., 2009). Priming studies have shown that processing morphologically complex words involves the sub-lexical segmentation of the word along its morphological boundaries (Diependaele, Grainger, & Sandra, 2011; Leikin & Zur Hagit, 2006). The importance of such segmentation at the morpheme level can be seen by its influence on word reading by aiding in the pronunciation of letter sequences, so that 'ea' is segmented and processed as one phoneme in the word 'reach' (which constitutes a single morpheme), while 'ea' is pronounced separately in 'react' due to its placement in two adjacent morphemes (Bowers, Kirby, & Deacon, 2010). Such segmentation at the morpheme boundary allows for the deconstruction of the word into its base form for an easier activation of the orthographic representations, thus influencing visual word recognition and bypassing the phonological route (Rastle & Davis, 2008).

Unlike phonemes or syllables, morphemes possess syntactic and semantic information. Such value-added information has been shown to aid in vocabulary acquisition (Carlisle, 2000; Nagy et al., 2006; Singson et al., 2000; Sparks & Deacon, 2013) and in the reading comprehension of children (Carlisle, 1995; Carlisle, 2000; Deacon & Kirby, 2004; Nagy et al., 2006) and adults (Nagy et al., 2006; Wilson-Fowler, 2011). Knowledge of frequent morphological units and the ability to segment along morpheme boundaries allows for the extraction of information from new or infrequently used words whose meanings may have been unknown. For example, when the suffix '-ian' is adjoined to a word such as 'music', creating 'musician', little past knowledge of the word 'musician' is needed for the reader to surmise that the target word is referring to a person who produces music.

The frequency of morpheme exposure has been shown to be vital in the development and utilization of morphological awareness. Nagy, Anderson, Schommer, Scott and Stallman (1989) found that in the reading of a morphologically complex word, the family size of the base word and its frequency within the reader's lexicon affects the speed of recognition of the target morphemes, which ultimately facilitates word recognition of familiar and unfamiliar words. Lazaro, Camacho and Burani (2013) showed a similar positive effect of base frequency in child readers, yet their results showed this benefit only for skilled readers. Such findings demonstrate how print exposure and vocabulary knowledge are explicitly linked to the development of the person's morphological knowledge. Correlations between the variables of morphological awareness and vocabulary have been repeatedly demonstrated across various languages and age groups (Fowler, Feldman, Andjelkovic, & Oney, 2003; Fowler & Liberman, 1995; Nagy et al., 2006; Singson et al., 2000). Such relationships have been shown to exist independent of phonological processing and word reading ability (McBride-Chang, Wagner, Muse, Chow, & Shu, 2005). Like many relationships related to language and reading development, the relationship between vocabulary and morphological awareness can be considered as bi-directional. Vocabulary knowledge has the potential to aid in the growth and development of a dyslexic's morphological awareness, for an increased vocabulary affords the individual the opportunity to gain familiarity with the morphological regularities in language. Such familiarity provides a greater resource base from which the reader can then extract morphological regularities and generalizable units. Accounting for such influences of vocabulary is paramount when examining individuals with dyslexia, for whom a resulting lack of print exposure has the potential to limit vocabulary growth.

In addition to supporting comprehension and vocabulary development, studies have asserted morphological awareness' contribution to word reading and to spelling abilities, independent of phonological awareness. Morphological awareness has been shown to independently explain 4-15% of the variance of word reading and nearly 7% of the variance in the spelling ability of elementary school children (e.g., Carlisle & Normanbhoy, 1993; Mahony et al., 2000; McCutchen, Green, & Abbott, 2008; Singson et al., 2000; Wolter, Wood, & D'Zatko, 2009) and in adults (Nagy et al., 2006; Wilson-Fowler, 2011).

To be considered as a means of compensation for individuals with dyslexia, morphological awareness needs to be independent of phonological awareness. Furthermore, morphological awareness must be shown to remain intact and a strength for individuals with dyslexia. Although research on morphological awareness of individuals with dyslexia has demonstrated a weakness in morphological awareness and processing compared to chronologically age match controls (Martin, Frauenfelder, & Cole, 2013; Tsesmeli & Seymour, 2006; Schiff & Raveh, 2007), several studies have demonstrated intact (or at least relatively intact) morphological skills in dyslexic readers. Studies comparing reading level matched controls with persons with dyslexia have shown similarities in several tasks of morphological awareness, implying that poor morphological processing is unlikely to be the cause of the observed reading deficits (Deacon, Parrila, & Kirby, 2008; Casalis et al., 2004; Egan & Pring, 2004). A training study by Arnbak and Elbro (2000) demonstrated that there was no significant correlation between the gains made in a dyslexic reader's morphological awareness and the extent of their phonological deficit. Arnbak and Elbro proposed that the often observed co-occurrence of poor phonological awareness and morphological awareness in individuals with dyslexia may be an indirect consequence of their reading disability resulting from their deficits in phonological awareness. Children with dyslexia who struggle early on with reading often end up with reduced print exposure resulting in less opportunity to develop adequate tools in noting morphological cues and knowledge (Joanisse, Manis, Keating, & Seidenberg, 2000; Fowler & Liberman, 1995).

Elbro and Arnbak (1996) presented two studies that provided evidence of the role morphological awareness is playing in compensation. In their first study, they found that dyslexic adolescents' reading speed benefited more from semantically transparent morphological structures than from control-matched words. This benefit and improvement of response times was found to correlate with improvements in reading comprehension. These results differed from the reading scores of matched controls who showed no benefit. The second study showed that dyslexics were significantly better at reading texts that were deconstructed and presented as morphemes compared to texts presented as syllables, whereas reading level controls showed a trend in the opposite direction. Leikin and Zur Hagit (2006) also found that adults with dyslexia benefited more from morphological priming than control readers did. They concluded that in the process of lexical access, compensated dyslexics may rely more on the slower morphological decomposition route than relying on orthographic or phonological codes for a faster whole word recognition.

This current study will firstly attempt to answer questions of how morphological awareness is represented and interacts with the phonological and literacy variables of adults with dyslexia. In this regard, we will explore morphological awareness' relationship to literacy skills and phonological processing. Secondly, we will evaluate morphological awareness' association to word reading, spelling and reading comprehension, independent of phonological awareness and vocabulary. Alongside this analysis, we will examine if the variance explained by morphological awareness is the same in both samples of adults with dyslexia and normal reading age matched controls. Finally, we will divide the dyslexic population into a group of compensated and a group of non-compensated dyslexics, and compare morphological awareness in both groups.

METHOD

PARTICIPANTS

The sample of participants was the same as presented in Law et al. (2014): 54 non-dyslexic and 36 adults with dyslexia. Participation required an official diagnosis of dyslexia produced during secondary school or earlier and completed by a registered and qualified clinical psychologist. The fact that the participants were selected from a university population, and given the selectivity of universities, a higher level of reading achievement was expected than those in a general sample of individuals with dyslexia of the same age. This is reflected in the normal reading and spelling scores of some individuals with dyslexia as seen in Table 1. Participants who have achieved higher than expected literacy scores might be considered as ‘compensated’ dyslexics.

The normal reading control population contained students with no documentation or history of reading difficulty. The dyslexic population was recruited in two English speaking universities in Ontario (Canada) through the University’s Student Services, while the control sample was obtained through class announcements and posters placed on campus at the same universities.

All participants were at least 18 years old and were native English speakers without a history of brain damage, language problems, psychiatric symptoms, hearing impairments or visual problems which could not be corrected for by a corrective lens. Additionally, all participants had an adequate nonverbal IQ as defined by a standard score greater than 85 on the Raven’s advanced progressive matrices. Groups did not differ in age, gender and nonverbal IQ. Participants’ characteristics can be found in Table 1.

Table 1: Participant characteristics

Measure	NR M	NR SD	DYS M	DYS SD	t	p
Age (years)	22.0	3.0	21.8	4.8	0.227	1
Non-Verbal IQ (APM)	112.7	9.9	107.0	20.7	1.777	.158
Literacy						
Reading[a] (SS) (WRAT-III)	106.1	5.8	91.7	10.1	8.575	< .002
Spelling[a] (SS) (WRAT-III)	107.6	6.6	90.8	8.8	10.305	< .002
Reading Comp. (WCJ)	40.0	2.6	36.9	3.0	-5.203	< .003
Morphological Awareness	19.7	2.3	14.5	3.8	8.024	< .002

Notes. All *p* values are Bonferroni adjusted for multiple comparisons. APM = Raven advanced progressive matrices; WRAT-III = Wide Range Achievement Test III. WCJ = Woodcock-Johnson III: passage comprehension sub-test. [a] Scores are standardized (M = 100, SD = 15). [b] Pearson Chi-Square value.

MATERIALS AND PROCEDURE

Literacy

Word reading and spelling was assessed by the WRAT-III reading and spelling sub-tests (Wilkinson, 1993).

Word reading. The reading sub-test required the participant to read aloud a list of 42 words. The participant received a single point for each correctly pronounced word to a maximum score of 42. The reliability coefficient for this WIAT–III subtest was obtained utilizing the split-half method and found to be .98. (Wilkinson, 1993).

Spelling. The spelling sub-test required the participant to accurately spell a series of dictated words. The words were presented orally by the test administrator and were followed by a sentence containing the word. One point was awarded for each correctly spelled word to a maximum score of 40 points. Reliability coefficient of this subtest was reported to be .97 (Wilkinson, 1993).

Reading comprehension. This was accessed by the use of the passage comprehension sub-test of the Woodcock-Johnson III (WJ-III) (Woodcock, McGrew, & Mather, 2001). Items required participants to read a short passage silently and identify the missing key word that would make sense based on the context of the passage. Items progressively increased in difficulty by increasing passage length, level of vocabulary, and the syntactic and semantic cue complexity. The WJ-III reports a median reliability of .88 for an adult population. Testing was discontinued when six consecutive incorrect responses were made or until the last test item was administered. Participants could obtain a maximum score of 47.

Phonological skills

Each aspect of phonological skills, as represented in Wagner & Torgesen (1987), was individually tested. Assessment methods followed the same procedures as those expressed in Law et al. (2014) and are described as follows:

Phonological awareness. Research has demonstrated spoonerism tasks' ability to significantly differentiate between an adult dyslexic population and control groups (Ramus et al., 2003). The assessment of phonological awareness (PA) utilized the spoonerism sub-test from the Phonological Assessment Battery (PhAB) (Frederickson, Firth, & Reason, 1997). In two parts, this task targeted onset-rhyme awareness and required phoneme manipulation and deletion. Target words were presented orally. The first task required the participant to replace the first sound of the word with a new sound (e.g. cot with a /g/ gives 'got'). In part two, participants were requested to transpose the onset of the sounds of the two words. For example, "plane crash" will become "crane plash" or "king John" becomes "jing kon". The PhAB reports a Cronbach's coefficient alpha of .89 for an adult population. Rate scores were calculated as the total correct responses divided by the total time required to complete the task creating a measure of correct items per second. Accuracy was not separately evaluated due to ceiling level achievement within the control group.

Rapid automatic naming. Two tasks were used in the assessment of Rapid Automatic Naming (RAN). First presented was a colour-naming test adapted from Boets Wouters, van Wieringen, and Ghesquiere (2006), which presented five colours (black, yellow, red, green and blue) in 5 rows containing 10 colour stimuli each. In addition, the object-naming sub-test from the Phonological Assessment Battery (PhAB) (Frederickson et al., 1997) was presented. This task used five line drawings of common objects (desk, ball, door, hat, box) in 5 rows each containing 10 items. Participants were asked to name aloud each of the objects or colours as quickly and as accurately as possible. A score of the number of symbols named per second was calculated.

Verbal short-term memory. Verbal short-term memory was assessed through the application of two tasks. Firstly, the number repetition (digit span forward) sub-test from the Clinical Evaluation of Language Fundamentals 4th ed. (CELF-4) (Semel, Wiig, & Secord, 2003) was administered. This task required the immediate serial recall of orally presented lists of digits between 2 and 9, spoken at a rate of one digit per second. List length increased incrementally from one to nine digits. The CELF-4 reports a Cronbach's coefficient alpha of .78 for a young adult population. The final score was the total number of correctly recalled lists with a maximum score of 16.

Secondly, the non-word recall (NWR) sub-test from the Working Memory Test Battery (WMTB) (Pickering & Gathercole, 2001) was administered. Each participant was instructed to repeat lists of orally presented single syllable nonsense words in the correct order. The reported test-retest reliability of the test is .68. List length was incrementally increased from one to six words. Final scores were calculated as the total number of correctly recalled lists with a maximum score of 36.

Vocabulary

To assess vocabulary the CELF4 word definitions sub-test was used. The participants were asked to define or describe the meaning of a word after it was presented orally alone and in a sentence. The CELF4 word definition subset offers 2- or 1-point criteria, which were used as the basis for scoring the participants' responses. If the response did not meet the 2- or 1-point criteria, a score of 0 was given. The CELF-4 reports a Cronbach's coefficient alpha of .86 for a adult population. A raw score for the sub-test was computed by adding the scores obtained for each item. The maximum score was 48.

Morphological awareness

Morphological awareness was measured through the use of a validated measure created by Willson-Fowler (2011). This morphological awareness task was designed for use with university students. The questions used in the test were selected after conducting an IRT on the university students' responses on three morphological awareness tasks. Willson-Fowler maintained 24 of the original 99 items in the creation of this task. These items were demonstrated to provide good discrimination and difficulty estimates in a university population. The selected morphological measure included items from two different types of tasks: a derivational suffix task and a non-word sentence completion task.

The derivational suffix task (DST). Items in the derivational suffix task were created by Willson–Fowller (2011) and were based on tasks created by Carlisle (2000) and Mahony's (1994) real word, multiple choice and sentence completion task. The task required participants to complete a sentence by applying a derivational suffix to a target root word (e.g., act: The secret police arrested the ________ before he could give his speech). Several studies have provided evidence relating the ability to read morphologically complex words to the frequency of the base word appearing in morphologically complex words (i.e., average family frequency; AFF). As a result all root words selected fell within an AFF range of 31.65 to 40.1 based on the standard frequency index (SFI). The frequency range of the selected derived words was 22.1 to 53.6 SFI. Stimuli included items which involved both phonological and orthographical changes. Some items contained only one change while others involved both. Instructions along with four examples were presented verbally and in writing. The items on this task measure syntactic and productive morphological awareness.

The non-word sentence completion task (NWSC). Items selected for the non-word sentence completion task were based on Mahony's (1994) study. Participants were instructed to read and complete incomplete sentences (e.g., They presented the highly ____ evidence first) from a selection list of four possible non-word choices that varied according to their real English suffixes (e.g., credenthive, credenthification, credenthicism, credenthify). The target words were equally divided between nonsense nouns, adjectives and verb derivatives. Instructions and one example were presented both verbally and in writing. Responses were scored as correct or incorrect.

Results

Performance of Adults with Dyslexia Versus Normal Reading Adults

Literacy

Results of the literacy tasks are found in Table 1. As expected, the normal reading adult group (NR) was found to perform significantly better than the dyslexic group (DYS) in both word reading and spelling.

Both literacy tests, the WRAT reading and spelling sub-test, were found to be normally distributed for both DYS and NR groups, as assessed by Shapiro-Wilk's test ($p > .05$). Homogeneity of variance was not found for either the reading or spelling, as assessed by Levene's Test for Equality of Variances ($p = .034$ and $p = .001$, respectively). Group comparisons revealed, however, a statistically significant difference in the mean scores of reading and spelling between both groups, $t(50.283) = 8.575$; $p < .005$ for reading, and $t(60.675) = 10.305$; $p < .005$ for spelling.

Phonological skills

The scores for the different aspects of phonological skills are presented in Table 2. Independent sample *t*-tests were run to determine whether the differences between groups in measures of phonological skills were significant. Scores of the NWR and Spoonerism tasks were not found to be normally distributed. In order to approach a normal distribution they were transformed by a square root transformation. Dyslexics were found to perform significantly poorer than the controls on all measures.

Table 2: Phonological abilities: descriptive statistics and *t* and *p*-values from independent

	NR		DYS			
Measure	M	SD	M	SD	*t*	*p*
Spoonerism (correct/sec)	0.23	0.08	0.10	0.04	9.042	< .005
Digit Span	12.32	1.87	10.78	2.00	3.712	< .005
Non-word recall	20.09	2.25	17.61	2.62	4.795	< .005
RAN (colour)	2.01	0.33	1.72	0.31	4.262	< .005
RAN (object)	1.77	0.24	1.50	0.25	5.059	< .005

Note. All *p* values are Bonferroni adjusted for multiple comparisons.

Morphological awareness

An ANCOVA was run to determine the effect of group differences in terms of normal and dyslexic readers on morphological awareness. After adjustment for vocabulary knowledge and phonology there was a statistically significant difference in the morphological awareness between the two groups: $F(1, 83) = 22.711$, $p < .001$, partial $\eta^2 = .215$.

Morphological Awareness' and Phonology's Contribution to Literacy of Dyslexic and Normal Readers

Table 3 displays Pearson correlations between all predictor and literacy outcome variables within each group. Morphological awareness differed in its relationships between the groups. Within the dyslexic group morphological awareness was found to have a positive relationship with reading and phonological awareness (measured with the spoonerism task) while these relationships were not found within the normal reading sample. As expected, vocabulary knowledge was shown to be closely related to morphological awareness in both groups.

To assess the contribution of morphological awareness to the literacy variables of word reading, spelling and reading comprehension, above vocabulary and phonological awareness, a series of hierarchal regressions was conducted. Separate regressions were performed within each group to understand whether or not morphological awareness can explain equal proportions of variance of word reading in adults with dyslexia compared to normal reading controls.

Three separate regressions were performed with word reading, spelling and reading comprehension as the outcome measure. In these analyses, vocabulary and phonological awareness were included as controls in steps one and two. In the control group these variables accounted for a total of 14.6% of the variance for word reading, 25.9% for spelling and 13.6% for reading comprehension. In step 3, the morphological awareness measure was entered into the regression equation. The results of these analyses are shown in Table 4 (a) for the normal reading control population and (b) for the dyslexic group. For the normal reading sample, morphological awareness contributed unique variance to spelling (19.4%) and reading comprehension (17.3%), yet not for word reading after controlling for the above-mentioned variables. In the dyslexic group, morphological awareness accounted for similar proportions of variance of spelling (17.4%) and reading comprehension (15.6%). However, the dyslexic group contrasted sharply with the control group in that morphological awareness was found to explain a significant proportion of the variance of word reading (16.5%) after controlling for the above-mentioned variables.

Table 3: Correlations between measures for phonology, morphological awareness, vocabulary and literacy skills (bottom left adults with dyslexia group, top right control group)

Measure	1	2	3	4	5	6	7	8	9	10
1. Read	--	.310*	.474***	.234	.352**	.130	.061	.227	.219	.345**
2. Spell	.389*	--	.228	.400**	.506***	.279*	.305*	.502***	.150	.432***
3. DS	.041	-.055	--	.454***	.436**	.200	.273*	.240	.183	.320*
4. NWR	.255	.217	.582**	--	.597***	.323*	.326*	.382**	.283*	.282*
5. PA	.401*	.243	.014	.074	--	.491***	.499***	.197	.203	.231
6. RANob	-.003	-.020	.056	-.019	-.144	--	.699***	.202	.137	.158
7. RANcol	-.052	.086	.219	.016	.112	.761***	--	.286*	.096	.161
8. Morph	.619***	.450**	.219	.370*	.489**	.068	.090	--	.488***	.534***
9. Vocab	.448**	-.020	.221	.183	.275	-.092	-.068	.367*	--	.318*
10. RComp	.665***	.140	.258	.402*	.306	.040	.011	.568***	.439**	--

Note. Read = WRAT reading; Spell = WRAT spelling; DS = Digit Span; NWR = non-word recall; PA = Spoonerism; RANob = RAN object naming; RANcol = RAN colour naming; Morph = morphological awareness; Vocab = CELF4 sub-test: word definitions; RComp = WCJ reading comprehension measure.

**p* < .05. ***p* < .01. ****p* < .001. $^{(*)}$Approaching significance of .05.

Table 4: Hierarchical regressions showing the unique variance in the word reading, spelling and reading comprehension accounted for by PA, vocabulary and MA (R^2change and standardized Beta)

(a) Normal reading age matched controls

Step	Read		Spelling		ReadComp	
	R^2 change	Beta	R^2 change	Beta	R^2 change	Beta
1. PA	.124**	.309	.256***	.443	.053	.123
2. Vocab	.022	.093	.003	-.180	.082*	.068
3. MA	.012	.125	.194***	.508	.173**	.481

(b) Dyslexic sample

Step	Read		Spelling		ReadComp	
	R^2 change	Beta	R^2 change	Beta	R^2 change	Beta
1. PA	.173*	.121	.059	.057	.098$^{(*)}$	.983
2. Vocab	.099*	.208	.006	-.204	.119*	-.030
3. MA	.165**	.484	.174*	.497	.158**	-.030

Note. Read = WRAT reading; Spell = WRAT spelling; PA = Spoonerism; Morph = morphological awareness; Vocab = CELF4 sub-test: word definitions; ReadComp = WJ-III passage comprehension measure.
*p < .05, **p < .01, ***p < .001, $^{(*)}$ Approaching significance of .05

Morphological Awareness and Compensation

To explore the contribution of morphological awareness to the achievement of normal word reading performance of some dyslexics, the dyslexic population was sub-divided into two groups. The two groups were labeled as non-compensated Dyslexics (NCDYS) (those who were found to still possess deviant performance on word reading achievement) and Compensated Dyslexics (CDYS) (those who have received a diagnosis of dyslexia in the past, but yet were able to achieve a non-deviant score on word reading). An individual was determined to be deviant on word reading if his/her measured performance fell below -1.65 *SD* from the established mean of the well-matched control sample. Group characteristics and differences of these two new sub-groups can be seen in Table 5. No alteration was made to the normal reading control population, whose characteristics are displayed in Tables 1 and 2.

An ANCOVA was used to examine any group differences between the normal readers and the non-compensated dyslexic and compensated dyslexic groups on measures of morphological awareness. Vocabulary was used as a covariate variable due to group differences found between the CDYS and NCDYS sub-groups. After adjustment for vocabulary there was a statistically significant difference in morphological awareness between the three groups, $F(2, 85) = 50.864$, $p < .0005$, partial $\eta^2 = .545$. Post-hoc analysis was performed with Bonferroni correction for multiple testing. Morphological awareness was found to be significantly greater in the normal reader group vs. NCDYS group ($p < .0005$) and the CDYS group ($p = .006$). The NCDYS group had the poorest performance on the morphological awareness task, which was significantly lower than the compensated group ($p < .0005$).

To isolate morphological awareness from phonology, group comparisons were made with the composite score phonology as a covariate alongside with vocabulary. With both vocabulary and phonology as covariates, a statistically significant difference between groups was still found, $F(2, 83) = 22.944$, $p < .0005$, partial $\eta^2 = .356$. The post hoc analysis (Bonferroni adjustment) differed from the original ANCOVA without phonology in that the compensated and normal reading groups were not found to have any statistically significant differences on their performance on the morphological awareness measure ($p = .179$) while the NCDYS sub-group remained significantly lower than both the CDYS group ($p < .0005$) and the normal group ($p < .0005$).

Regression analysis was not performed within the sub-groups of compensated and non-compensated dyslexics due to the small sample size.

Table 5: Participant characteristics for dyslexic (DYS) and compensated dyslexic (CDYS) sub-groups

	CDYS		DYS			
Measure	M	SD	M	SD	*t*	*p*
Gender (f/m)	11/4		15/6		.016[b]	.602
Age (years)	22	1.9	22	6.1	.523[c]	1
Non-Verbal IQ (APM)	112.7	11.9	102.8	24.6	-1.467[c]	.760
Vocabulary (Raw)	40.9	2.3	37.2	3.5	-3.537[c]	.005
PA (z-score)	-1.49	1.1	-1.82	.60	-1.100[c]	1
MA	17.6	1.3	12.4	3.6	-5.161[c]	<.005
Word-reading[a]	101.6	5.8	84.7	5.8	-8.870[c]	<.002
Spelling[a]	92.8	8.7	89.3	8.8	-1.168[c]	.251
Reading Comprehension	39	2.1	35.1	2.3	-5.513[c]	<.002

Note. All *p*-values are Bonferroni adjusted for multiple comparisons.
APM = Raven Advanced Progressive Matrices. MA - Morphological Awareness [a] Scores are standardized ($M = 100$, $SD = 15$), [b] Pearson Chi-Square value, [c] *t*-value.

Discussion

The present study examined the nature of the relationships between morphological awareness, phonological skills, word reading, spelling and reading comprehension in adults with dyslexia and age-matched adult controls.

Consistent with much of the literature on dyslexia, the dyslexic sample was found to have a significantly poorer performance on measures of phonological processing, spelling, word reading and reading comprehension when compared to a normal reading population (Vellutino, Fletcher, Snowling, & Scanlon, 2004). In addition, adults with dyslexia were found to perform poorer on tasks assessing morphological awareness than age-matched controls; such findings support earlier research in children (Carlisle, 1995; Carlisle, 2000; Deacon & Kirby, 2004; Nagy et al., 2006) and adults (Nagy et al., 2006; Leikin and Zur Hagit, 2006). Within the dyslexic sample, relationships across the variables that were found to be deviant were examined and revealed morphological awareness' significant relationship with all literacy measures and vocabulary. Of these relationships, the one found existing between morphological awareness and word reading was the strongest. In terms of morphological awareness' relationship with phonological skills, only phonological awareness and non-word recall were found to be related to morphological awareness in this sample. These findings support previous developmental studies of children that have suggested the interrelationship of these two variables (Carlisle, 1995; Casalis et al., 2004; Nagy et al., 2006; Roman et al., 2009). Studies have found that these variables, although correlated, are distinct literacy skills, with morphological awareness having a longer developmental trajectory than phonological awareness (Berninger, Abbott, Nagy, & Carlisle 2010; Deacon & Kirby, 2004; Jarmulowicz et al., 2008; Kirby et al., 2012). It is thought that morphological awareness is a late-emerging skill that is built upon an individual's phonological awareness (Seymour, 1999; Casalis et al., 2004; Ehri, 2005). Based on the supposed influence of phonological awareness on the development of morphological knowledge, phonological awareness was used as a control variable throughout all analyses of this study.

To understand morphological awareness' independent contribution to the assessed literacy variables, a regression analysis was conducted controlling for both phonological awareness and vocabulary knowledge.

Morphological awareness was found to contribute to spelling and reading comprehension in both the normal reading and dyslexic sample. The results were different for word reading. The regression analysis demonstrated a larger interaction between morphological awareness and word reading ability in adults with dyslexia when compared to the normal reading population. For the dyslexic readers, 16.7% of the variance in word reading was accounted for by morphology, while phonological skills were not found to provide any statistically significant contribution. This relationship was in stark contrast to the normal readers, where morphological awareness was not found to significantly explain any variance of word reading above that of phonology's 12.4%. Two differing and competing conclusions could be drawn from these results.

The first, and least likely of the two conclusions, is that difficulties in morphology are in part responsible for the observed reading difficulties in dyslexics. Leikin and Zur Hagit (2006) suggested that a deficit in the morphological awareness of dyslexics together with a significant contribution of morphological awareness (independently of phonological awareness) to word reading, could be taken as evidence of deviant morphological awareness skills thus contributing to the observed literacy difficulties of dyslexics. Although a reasonable argument, few researchers would support the idea that morphological awareness is a causal factor in dyslexia. In addition, counter evidence of intact morphological skills of individuals with dyslexia has been provided by reading age matched studies demonstrating equal and/or better performance of dyslexics in spelling (Bourassa, Treiman, & Kessler 2006; Bruck, 1993) and reading (Carlisle & Stone, 2003; Elbro & Arnbak, 1996; Joanisse et al., 2000; Martin et al., 2013). Such results suggest that the observed deficit in morphological awareness is more likely to be secondary to the more primary deficits of phonological processing and reading ability.

The second possible conclusion is that adults with dyslexia have made a shift in the underlying cognitive mechanisms of word reading. When results of the regression analysis between both sample groups are compared, the dyslexic group exhibited a shift away from an association between phonological skills and word reading – as represented in the control group – to a greater involvement of morphological awareness. A phonological deficit, as observed in the dyslexic population, is believed to impede sub-lexical processing and the reading of new or unfamiliar words. As discussed by Taft (2003), the nature of written morphemes allows for segmentation of morphologically complex words into their constituent parts (base, prefix, suffix) allowing for an alternate path of sub-lexical processing ultimately facilitating word reading by minimizing dependence on phonological processing.

If a stronger reliance on morphological knowledge were to be utilized by adults with dyslexia as a compensatory mechanism, then it would be expected that adults with dyslexia, who are able to compensate and achieve normal levels of word reading, would also possess stronger morphological awareness skills than non-compensated dyslexic adults. Although dyslexia by definition is a reading impairment, not all dyslexics included in our study demonstrated deviant performance on the word reading measure. While all dyslexic participants had received an early diagnosis of dyslexia, compensatory factors and strategies could explain their word reading success. To evaluate our proposed theory of morphological awareness' role in the compensation process, the dyslexic population was subdivided into two groups: compensated dyslexics (those whose reading scores were no longer found to be deviant) and non-compensated dyslexics (those whose reading scores were still deviant). The two groups did not differ significantly in IQ, age, or phonological skills, yet group differences were found in vocabulary and morphological awareness.

Surprisingly, after differences in vocabulary and phonological skills were controlled for, no statistical difference could be observed in morphological awareness between the normal reading and the compensated dyslexic groups, while the non-compensated group differed from both other groups. Linked with the earlier discussed finding of morphological awareness' significant contribution to reading outcomes in the dyslexic sample, one can conclude that intact and strong morphological awareness skills are directly associated to the achieved compensation of these dyslexics. Such a notion of morphology playing an active role in the compensation of dyslexics is not new and is consistent with past research. Elbro and Arnbak (1996) demonstrated that compared to reading age matched controls, dyslexics benefited significantly more from reading a text segmented into morphemes than from a text segmented into syllables. The same paper also presented findings showing that dyslexic adolescents were reading words containing semantically transparent morphological structures faster than matched words.

EDUCATIONAL IMPLICATIONS

In support of previous adult studies, our results have expressed morphological awareness' importance in explaining the variance of word reading in adults with dyslexia along with explaining a significant portion of spelling and reading comprehension across both groups of adults (Nagy et al., 2006; Tighe & Binder, 2013; Wilson-Fowler, 2011). Linked with the evidence of strong and intact morphological awareness skills of compensated adult dyslexics, these results demonstrate the potential of intervention and remediation programs for adult dyslexics. It has been estimated that nearly 60% of all unfamiliar words an individual encounters beyond middle school are morphologically complex. Explicit instruction on how to utilize the tools of the morphological properties of these words would allow the dyslexic reader to read and extract meaning from a word (Nagy et al., 1989). As demonstrated by intervention studies in children, the explicit teaching of morphological knowledge can improve morphological awareness and vocabulary, ultimately having a positive effect on word reading, spelling and reading comprehension. Children with special literacy needs have been shown to benefit as much or more from morphological training than their normal reading peers (Bowers et al., 2010; Nagy, Carlisle, & Goodwin, 2014). The instruction and creation of strong morphological skills could provide a possible tool for adults or children with dyslexia to bypass their poor phonological skills and utilize the morphological structure and larger lexical units of morphemes which can then be generalized across a word and which contain added value of semantic and syntactic information compared to syllables and phonemes. Recent calls for the development of such intervention programs have been made and supported by Nunes and Bryant (2006) and Tighe and Binder (2013). Yet, longitudinal intervention studies of an adult dyslexic population are needed to understand the best means of instruction and to explore which aspects of morphology are most beneficial to an adult population.

LIMITATIONS OF THE PRESENT STUDY

A limitation of the current research is that only production tasks involving sentence completion were utilized in the assessment of morphological awareness, and therefore, our results can only be generalized to implicit morphological awareness with the aid of sentence context. The lack of diversity in the testing battery of this study may have limited the ability to fully capture the potential and different underlying dimensions of morphological awareness. Differences in task design and in the measuring of morphological awareness have produced some conflicting results regarding the role and strength of morphological awareness in the reading process of dyslexic individuals. For example, explicit tasks such as those involving the segmentation and manipulation of morphemes are not able to replicate strengths of dyslexic participants in morphological production tasks (Elbro, 1990; Casalis, 1987; Casalis et al., 2004).

It is noted that the prediction of word reading by the used RAN measure may have been stronger with the use of the alphanumeric sub-test which had been replaced by the colour naming task in order to be in line with other ongoing research.

Another limitation of this study is the limited focus of the word reading measure. Alternate conclusions could have been drawn with the inclusion of pseudo-word reading, reading speed, and/or specially tailored morphologically complex word reading tasks. The inclusion of a more diverse testing battery in future research will allow for a finer grained analysis and understanding of how specific aspects of morphological awareness aid in compensation.

Conclusions

The results of this study indicate that morphological awareness is an important predictor of dyslexic adult word reading, spelling and reading comprehension over and above the influence of phonological awareness and vocabulary knowledge. The findings that compensated adults with dyslexia possess similar levels of morphological awareness as normal readers (when differences in phonological skills are controlled for), indicates not only intact morphological processing, but also its relative strength and possible aid in this subgroup's achievement of normal levels of word reading. In line with previous studies implicating morphology as a possible compensatory variable, our study further supports the need for the development and study of interventions explicitly targeting the morphological awareness skills of adults with dyslexia. The explicit teaching of morphological rules and methods for the morphological decomposition of words could potentially improve adult dyslexics' morphological awareness; subsequently, improving their word reading skills. Although its potential to help individuals in overcoming their reading difficulties is promising, further research is still needed to fully understand morphological awareness' role in compensation and how to effectively direct such target interventions.

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CHAPTER 4

A study of MA, PA and Auditory Processing in pre-readers with a family risk of dyslexia[3]

Phonological awareness's direct influence on reading outcomes has been widely demonstrated, yet PA may also exert indirect influence on reading outcomes through other cognitive variables such as morphological awareness (MA). However, PA's own development is dependent and influenced by many extraneous variables such as auditory processing, which could ultimately impact reading outcomes. In a group of pre-reading children with a family risk of dyslexia and low-risk controls, this study set out to answer questions surrounding PA's relationship at various grain sizes (syllable, onset/rime and phoneme) with measures of auditory processing (frequency modulation (FM) and an amplitude rise-time task (RT)) and MA, independent of reading experience.

Group analysis revealed significant differences between high- and low-risk children on measures of MA, and PA at all grain sizes, while a trend for lower RT thresholds of high-risk children was found compared with controls. Correlational analysis demonstrated that MA is related to the composite PA score and syllable awareness. Group differences on MA and PA were re-examined including PA and MA respectively as control variables. Results exposed PA as a relevant component of MA, independent of reading experience.

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INTRODUCTION

Developmental dyslexia, a hereditary neurodevelopmental disorder, is characterised by severe reading and/or spelling impairments that are persistent throughout life (Vellutino, Fletcher, Snowling & Scanion, 2004). Research has suggested that the poor decoding abilities observed in people with dyslexia stem from a cognitive deficit in the development of, and/or access to, phoneme representations (Snowling, 2000; Tönnesen, 1997, but see Ramus & Szenkovits, 2008). Such observations have led to the development of the phonological deficit theory of dyslexia. Evidence of the past decade has suggested that a more fundamental deficit in auditory processing is underlying the phonological deficit, leading to the auditory temporal processing deficit theory of dyslexia (Boets et al., 2007; Goswami et al., 2002; Tallal, 1980). This theory postulates that a deficit in the processing of dynamic auditory stimuli negatively impacts the perception of syllables and phonemes, leading to a disruption of the development of suitable phonological representations (Poelmans et al., 2011).

Although phonological processing deficits have been found to describe a significant portion of the variance in reading by dyslexics, a large proportion of the variance still remains unexplained. As a result recent theories of dyslexia have highlighted the possible existence of a multitude of interacting deficits. It is thought that individuals' expressed behavioural deficits may be a function of multiple cognitive factors acting as risk or protective factors, independently or in conjunction with the phonological deficit (Pennington, 2006). Such insights have led the exploration of alternative cognitive variables to account for the observed problems in the reading and spelling of persons with dyslexia. Morphological Awareness (MA) is one such variable that has begun to be recognized as a contributing variable in word recognition, independent of orthographic processing, phonological awareness, rapid automatized naming, and vocabulary (Carlisle, 2000; Deacon & Kirby, 2004; Kirby et.al., 2012). Yet disagreement exists as to the role of MA within the dyslexic population. Is MA merely a function of the dyslexic readers poor PA skills and reduced reading experience (Carlisle, Colé, & Sopo, 2004; Deacon, Parrila, & Kirby, 2008), or does MA play a possible compensatory role in the poor reading abilities of persons with dyslexia (Elbro & Arnbak, 1996; Law, Wouters & Ghesquière 2015; Leikin & Zur Hagit, 2006)? A better understanding of how early MA relates to the phonological skills of children with dyslexia during their pre-reading phase could help in disentangling the relationship of reading experience, PA and MA.

The aim of this study is twofold. First, in a group of pre-reading children with a family risk of dyslexia and low-risk controls, we will analyze how the phonological deficit is expressed at various grain sizes of PA (onset/rime, syllables and phonemes) and how PA proficiency at each of these grain sizes relates to measures of auditory temporal processing. Such analysis allows for an assessment of the auditory temporal processing theory of dyslexia and helps to demonstrate the relationship between measures of auditory temporal processing and PA proposed by the theory, thus answering questions about the role of deviant auditory processing as a risk factor for a deficit in phonological development.

Secondly, the relationship between the various PA and MA skills will be explored in an attempt to shed light on the pre-reading relationship of MA and PA, specifically addressing questions regarding the role of early PA on the development of MA.

Phonological awareness

A child's phonological awareness (PA), the ability to recognize, isolate and manipulate the basic sound units of a language, begins to develop early in life. Prior to reading instruction, the development of phonological awareness begins with the explicit awareness of larger grain size units (syllables and onset/rimes). Only after explicit instruction do children develop smaller grain size representations at the level of the phoneme thus establishing phonemic awareness (Ziegler & Goswami, 2005). This developmental progression has been shown to have neurological foundations (Vanvooren, Poelmans, Hofmann, Ghesquière & Wouters, 2014). In a 2014 study of pre-reading children, Vanvooren and colleagues noted mature hemispheric specialization for processing syllable rate modulations in pre-reading children, while hemispheric specialization for phoneme rate modulation processing appeared to be still developing.

Phonological awareness skills have been shown to be vital in later reading and spelling achievement across both transparent and opaque orthographies. Pre-reading phonological awareness has been demonstrated to account for 40%-60% of the later reading achievement of kindergarten children (Bryant, MacLean, Bradley, & Crossland, 1990; Caravolas, Hulme, & Snowling, 2001; Wagner, Torgesen, & Rashotte, 1994).

Deficits in phonological awareness are often characteristic of dyslexia. Early pre-reading deficits in PA have been observed in children at high risk of, or later diagnosed with, dyslexia (Elbro et al., 1998; Pennington & Lefly, 2001; Snowling et al., 2003). This deficit has been shown to persist after the onset of reading instruction (Boets et al., 2010; Dandache et al., 2014; Snowling, Muter, & Carroll, 2007). Research over the past decade has begun to suggest that the observed phonological deficit of dyslexic readers is linked to a more fundamental deficit in auditory processing (Boets et al., 2007).

Auditory temporal processing and dyslexia

Spoken-language comprehension and processing is dependent on the accurate isolation and interpretation of meaningful units of speech such as words, sentences or utterances. Such high-level perceptual units are an amalgamation of basal acoustic-phonetic cues that can be categorized within various time scales corresponding to various phonological grain size units. For example, syllable recognition is reliant on time windows corresponding to a range of 3-7 Hz while shortened time scales of 12-50 Hz corresponds to segmental information related with phoneme identity (Goswami et al., 2011; Obrig, Rossi, Telkemeyer, & Wartenburger, 2010). It is believed that during the pre-literate phase of development, the attainment of well-specified sub-lexical phonological representations is dependent upon the accurate perception and processing of acoustic cues signalling syllable and/or phoneme specific time windows in speech. Therefore, it is reasonable to assume that an individual with an impairment relating to the processing of these low-level auditory temporal cues would be limited in their ability to reflect upon—and isolate—the basal phonological information of words in speech, thus resulting in inaccurate phonological representations (Boets et al., 2007; Goswami et al., 2002; Tallal, 1980).

In the past decade, various auditory parameters have been used in research to explore the relationship between impaired auditory processing and the phonological deficit associated with dyslexia. In a recent review, Hämäläinen and colleagues showed that group differences between dyslexics and controls were most often observed in studies that utilized slow rate (<60 Hz) sound parameters of frequency modulation (FM) and measures of amplitude rise time (RT) (Hämäläinen, Salminen, & Leppanen, 2012). In this review, encompassing an age range of 8.8-37 years, significant group differences between dyslexics and controls were found for 100% of the studies utilizing RT stimuli and 92% of the FM studies.

Significant group differences have been shown to exist between dyslexics and controls on measures of FM detection. Such studies have revealed that dyslexics have a reduced sensitivity compared to the control group, thus demonstrating the FM task's ability to differentiate between adult, school-aged children and pre-reading dyslexics from normal readers (Boets et al., 2007; Ramus et al., 2003; Witton et al., 2002; Witton et al., 1998). In addition, phonological decoding skills of adults with dyslexia and controls have been found to significantly correlate with FM sensitivity of 2 and 40 Hz (Witton et al., 1998). Similarly, Hämäläinen et al. (2012) noted eight separate studies that reported correlations between FM detection thresholds and reading and/or spelling skills, while three studies were unable to replicate these results (Dawes et al., 2009; Heath et al., 2006; Van Ingelghem et al., 2005).

Unlike FM tasks, amplitude rise time (RT) tasks assess an individual's perceptual sensitivity to the rate of change of the onset of the amplitude envelope, a temporal cue associated with the signalling of the onset of new syllables. Detection of such linguistic markers is thought to be important in speech perception and in early phonological development (e.g. Goswami et al., 2011; Goswami et al., 2002; Poelmans et al., 2011). Detection of such cues has been shown to be significantly associated with the reading, writing and phonological skills of adults (Corriveau et al., 2007; Hämäläinen et al., 2005; Law, Vandermosten, Ghesquière & Wouters, 2014) and children (Corriveau et al., 2010; Goswami et al., 2002; Poelmans et al., 2011). One of the few studies that has assessed RT in a group of pre-school children demonstrated the early importance of RT sensitivity in developing phonological awareness skills, specifically rhyme awareness (Corriveau et al., 2010).

Morphological awareness

Morphological Awareness (MA), often described as the explicit awareness and ability to manipulate and reflect upon the morphemic structure of words, has been shown to exist already in pre-reading children (Berko, 1958; Carlisle & Fieldman, 1995; Lyytinen & Lyytinen, 2004). Recent studies have recognized MA as a contributing variable in word recognition and reading comprehension, independent of orthographic processing, phonological awareness, RAN, and vocabulary (Carlisle, 2004; Deacon & Kirby, 2004; Kirby et al., 2012; Roman, Kirby, Parrila, Wade-Woolley & Deacon, 2009).

In English, morphological awareness aids in the identification, comprehension and pronunciation of words by the analyses of their component morphemes. A review paper by Bowers et al. (2010) highlighted how the implicit awareness of morphemic boundaries influences the pronunciation of letter sequences, thus aiding decoding. Bowers et al. presented the boundary between 'ea' as an example. In the case of the word 'reach', which composes a single morpheme, the letter combination is segmented and processed as one phoneme. While for 'react' the 'ea' is pronounced separately due to its placement in two adjacent morphemes. In addition, comprehension is aided through syntactic and lexical information provided by the suffix and prefix, allowing the reader to learn new morphologically complex words (Nagy, Berninger, & Abbott, 2006).

Research has shown MA begins developing prior to reading instruction. Studies utilizing oral tasks have demonstrated morphological awareness in pre-reading children of four-years-old (Berko, 1958). Berko used an oral, non-word completion task that required children to apply morphemes on a target non-word to complete the sentence (i.e. Here is one WUG; now look there are two of them, there are two _____ [WUGS]). Children as young as four-years-old were able to complete this task, yet some struggled on tasks requiring more complex morphological transformations, indicating an incomplete development of their morphological awareness. Often, anecdotal evidence is cited as evidence of preschool children possessing an implicit ability to produce some derived forms, such as 'flyable' or 'gooder'.

Carlisle and Fleming (2003) showed that morphological awareness progressively develops with age and through increased print exposure. Reading experience introduces a wider range of morphologically complex words, which stimulates and expands an individual's morphological awareness (Nagy and Anderson, 1984). Five to six-year-old children were found to be able to decompose familiar words into their constituent morphemes but could not explicitly account for the lexical or syntactic information contained within the affixes. However, by grade 3, these skills had improved (Carlisle & Fleming, 2003). Studies have shown that the contribution of morphological awareness to reading ability also changes and strengthens with development (i.e. Singson, Mahony, and Mann, 2000).

Cunningham and Carroll (2013) highlighted two distinct theories that have been put forth in the literature regarding the early development and predictors of MA. The first depicts early MA development as a function of a broad base of oral language skills. As a child’s oral vocabulary grows, they are able to link generalizable morphological units that are shared between words. The isolation and extraction of these units, therefore, allow for the development of an awareness of morphemes (i.e. –ing as in jumping and running). Correlational evidence has been provided supporting this theory (Kieffer & Lesaux, 2012; Nagy et al., 2006). However, directionality cannot be implied through correlations. In a study of preschool children, McBride-Chang et al. (2005) provided evidence of a reciprocal relationship between vocabulary and morphology, showing that gains in one variable led to gains in the other. An alternative theory, discussed by Carlisle & Nomanbhoy (1993) and later elaborated by Chiat (2001), implicates a child’s phonological skills in MA development. The theory argues that phonological processing is not merely limited to the lexical and sub-lexical segmentation and representation, yet it is implicated in the development of syntactic and semantic aspects of oral language, thus influencing MA development. Chiat reasoned that while acquiring language, young children are presented with a stream of speech set in, and related to, the context of a specific environment. The child is required to segment the stream of speech recurrently until (s)he is able to identify usable meaningful phonological components. In addition, the child must understand the context and environment in which the phonological unit is isolated from speech. This awareness permits the creation of mappings between potential semantic, syntactic and phonological information, which allows for morphological learning to take place. For example, in the acquisition of the morpheme –ing, the child must first be able to recognize and process the phonological information of this speech unit when spoken. As well, the child must recognize that this speech unit often co-occurs with action being undertaken presently in the environment (i.e. “look at the man jumping” while a man is seen jumping). As children’s phonological awareness develops and they become aware of the phonemic structure of language, further morphological learning is permitted. For instance, greater phonological sophistication aids in the learning of morphophonemic rules that are required to understand the phonological shifts often made during the application of a suffix (e.g. divide and division, invade and invasion) (Carlisle & Nomanbhoy, 1993).

This theory has been supported by Cunningham and Carroll (2013) who found that pre-reading phonological processing predicted grade one morphological awareness and strategy use for spelling and non-word reading. Similarly, Carlisle and Nomanbhoy (1993) found that kindergarten PA (as measured through syllable and phoneme deletion) could predict expressive MA after controlling for vocabulary. Intervention studies of typically developing kindergarten children and those with speech impairments have also demonstrated gains in MA skills through PA instruction (Casalis & Cole, 2009; Kirk & Gillon, 2007).

Based on these competing theories, it is reasonable to assume that the phonological impairment of children with dyslexia would result in poor morphological development and early MA attainment, or in contrast, MA could independently develop in the context of literacy acquisition and the semantic and syntactic units conveyed in oral language (Casalis, Cole & Sopo, 2004).

People with dyslexia have been found to have a significantly poorer performance on many morphological production tasks when compared with chronologically age-matched controls (Casalis et al., 2004; Fowler, Liberman and Fieldman, 1995; Shankweiler et al., 1995). Yet, when compared with reading-age matched controls, no differences could be found (Casalis et al., 2004; Elbro, 1989; Fowler, Liberman & Fieldman, 1995). The observed phonological impairments of dyslexic children have been shown to prevent the explicit segmentation of affixes while leaving productive morphological knowledge development unaffected; suggesting a dependency of morphological awareness development on reading experience and phonological skills (Casalis et al., 2004). Because the PA deficit of people with dyslexia greatly influences later reading experience, the study of a dyslexic's morphological awareness in a pre-reading population would be required to determine the relationship the phonological deficit has with the development of MA in dyslexic children.

Objectives and goals of study

The objective of this study is to explore pre-reading MA, PA and measures of auditory temporal processing in children with a family risk of dyslexia. First, we will explore how our high- and low-risk groups fit with the current cognitive theories of dyslexia, as pertaining to poor phonological representations. Group differences of the three aspects of phonological processing, phonological awareness (PA), verbal short-term memory, and lexical retrieval (Wangner & Torgesen, 1987) will be assessed to explore if high-risk groups demonstrate a deficit in the phonological domain, as predicted by the phonological deficit theory of dyslexia.

In addition, the study will assess whether the phonological deficit is present at various grain sizes of PA in a pre-reading population. Further, the relationship between different measures of auditory temporal processing (RT and FM) and the various grain sizes of PA will be studied in order to test the proposed auditory temporal processing deficit theory of dyslexia. This study will also evaluate pre-reading MA in children of HR and LR groups and its relationship to PA at various grain sizes. Older, literate dyslexic children are found to differ from age-matched controls on MA measures, yet no differences in their MA performance are found when compared with reading age matched controls. Poor MA skills observed in populations of dyslexics are often attributed to their reading experience, and/or as a result of their poor PA. By examining the relationship of PA and MA prior to formal reading instruction, we can help disentangling MA's debated relationship with reading experience and PA.

Method

Participants

A group of 58 preschool children ranging in age from 4 to 5 years old and attending Senior Kindergarten (SK) in the Ontario, Canada public school system were selected for the study. Children were classified as either being at high-risk (HR) for developing dyslexia (N=23), or as low risk (LR) (N=35). Due to dyslexia's tendency to run strongly in families, the high-risk group was selected based upon the child having at least one first-degree family relative with an official diagnosis of dyslexia. The low-risk group was matched to the high-risk group based upon measures of intelligence, socioeconomic status, gender, age and educational environment. High-risk children were selected for participation based on their meeting of the criteria: having at least one first-degree family relative possessing a formal diagnosis of a reading disability (i.e. dyslexia); possessing no signs of brain damage or long term auditory or visual impairments; and being a native

English speaker born in 2008 and entering the second year of kindergarten (SK).

Recruitment involved the distribution of letters of invitation to families of pupils a few months before entering SK. Parents were requested to complete an online questionnaire to investigate the general development, medical history and the behaviour of the participating child, along with evaluating the family history of reading and spelling (dis)abilities of the family members. The potential existence of ADHD and behavioural problems was additionally screened by the inclusion of a hyperactivity measure consisting of questions taken from the Strengths and Difficulties Questionnaire (SDQ) (Goodman, 2001). Through information gained from the parental survey children with a history of brain damage, language problems, psychiatric symptoms, visual problems or hearing loss were excluded from the study Additionally, the questionnaire assessed the educational level through the use of the seven point ISCED-scale (International Standard Classification of Education by UNESCO, 1997). The various educational levels represented in the scale were then further simplified into three educational categories: secondary school (Sec), post-secondary (PS), graduate studies (GS). Groups were found not to differ on measures of age, IQ, hyperactivity and SES and parental educational level as seen in table 1.

As testing occurred within the first two and a half months of Senior Kindergarten, all participating children had not received any formal reading instruction prior to their testing date. Therefore, for the purposes of this study these children will be considered as pre-reading.

Table 1: Participant characteristics

	NR (n=35)	DYS (n=23)	*p*-value
Gender (F/M)	17/18	12/11	.115[b]
Age in months (mean ± SD)	64.3 ± 4.1	62.7 ± 2.2	.090[c]
Non-Verbal IQ[a] (mean ± SD)	107.1 ± 8.1	106.0 ± 6.3	.565[c]
Hyperactivity (mean ± SD)	2.9 ± 1.6	3.6 ± 2.3	.205[c]
SES (ISCED) (low/middle/high)	1/21/13	2/13/8	.671[d]
Mother’s education (Sec/PS/GS)	7/21/7	2/16/5	.588[d]
Father’s education (Sec/PS/GS)	7/22/6	4/15/4	1.00[d]

Notes: [a] Scores are standardized (M = 100, SD = 15). [b] Pearson Chi-Square value. [C] Paired t-test . [d] Fisher’s Exact Test. Sec = secondary school education, PS = post-secondary education, GS= graduate studies

Materials and Procedures

Socioeconomic status (SES)

SES was assessed with the Family Affluence Scale II (FAS II), developed by the World Health Organization (WHO). The FAS II is a four-part measure of family wealth scored as a composite measure ranging from 0-9. Similarly to Boyce, Torsheim, Currie and Zambon (2006), initial scores were transformed into 3 categories of low affluence (0-2), middle affluence (3-5) and high affluence (6-9).

Intelligence (IQ)

The Raven's Coloured Progressive Matrices (Raven, Court & Raven, 1998), a collective non-verbal intelligence test measuring spatial reasoning, was administered. This test measures an individual's ability to reason and solve problems, without the benefit of prior knowledge and is specifically designed for children and older adults. The test consists of 36 items in 3 sets, which produces a single raw score that is converted to a percentile score based on provided norms.

Letter knowledge and literacy measures

Both receptive and productive letter knowledge tests were administered through the letter writing and naming subtests of the Wide Range Achievement Test (WRAT3). For each test the 15 most frequently used letters in English books for children were used.

Productive letter knowledge: The fifteen letters (printed in upper case graphemes) were presented to the child. The child was instructed to verbally produce the letter name and/or sound produced for each of the 15 graphemes. One point was attributed to each correct answer resulting in a maximum score of 15.

Receptive letter knowledge: Fifteen common letters were presented orally. The child was required to record each spoken letter by writing it on the record sheet. A point is given for each correct response allowing for a maximum score of 15.

Phonological awareness (PA)

A subtest of the Clinical Evaluation of Language Fundamentals 4th ed. (CELF-4) (Semel, Wiig and Secord, 2003) was selected to assess each participant's phonological awareness ability at various grain size levels. The subtest contains 11 elements: syllable blending (SB), two syllable deletion (2SD), final syllable deletion (FSD), three syllable deletion (3SD), syllable segmentation (SS), rhyme detection (RD), rhyme production (RP), phoneme blending (PB), initial phoneme identification (IPI), medial phoneme identification (MPI), final phoneme identification (FPI).

Verbal short-term memory

The Number Repetition* subtest** from The Clinical Evaluation of Language Fundamentals 4th ed. (CELF-4) (Semel, Wiig and Secord, 2003) was selected to assess verbal short-term memory. This is a digit span forward task, requiring the immediate serial recall of orally presented series of digits with lengths of 2 to 9 digits. To avoid any influence arising from differences in prior digit knowledge the subjects were asked to count from 1 to 10 to familiarize themselves with the required stimuli. All children were found to be able to complete this initial task. The test score was calculated as the total number of correct recalled lists. In addition, ***The non-word repetition test from the Phonological Assessment battery (PhAB) (Frederickson, Firth, & Resaon 1997) was employed. For this task, sequences ranging in length from 2 to 6 single syllable nonsense words were presented orally to the participants. Each participant was requested to repeat the sequence in the correct order. The sequences progressively increased in length. Students could reach a maximum score of 36.

Lexical retrieval

Two naming tasks were administered to assess speed of phonological production through the retrieval of whole-word level phonological coding. Final scores of both tests were calculated as correctly named items per second.

A colour naming test from Boets et al. (2006) was selected for the purposes of this study. Five colours (black, yellow, red, green and blue) were presented in a random arrangement on a single sheet of paper arranged in 5 columns of 10 colour stimuli each.

The object naming subtest of the Phonological Assessment Battery (PhAB) (Frederickson, Frith and Reason 1997) was used. Five line drawings of common objects (desk, ball, door, hat, box) were presented in 5 rows, each containing 10 items.

Morphological Awareness

Morphological awareness was assessed using the Wug test to evaluate the individual's ability to apply morphological change to mark inflections and derivations along with the use of appropriate possessive relationships. The 'Wug test', first developed by Berko (1958), uses target non-words which have been created to be plausible sounding English words. In the Wug test a child is shown a simple picture depicting a creature or activity and is prompted to complete a statement which requires the addition of a morpheme to the target pseudoword: "This is a WUG. Now there is another one. There are two of them. There are two _______." (Response: WUGS). A maximum score of 33 could have been obtained.

Auditory processing tasks

All tasks were conducted at the child's school and administered individually in a private room, with minimal ambient background noise and distraction. To further reduce any influence of ambient noise over-the-ear Sennheiser HDA 200 headphones were used to present the stimuli, which offered a level of passive noise reduction. All auditory tasks were performed on a Dell Latitude D510 and controlled by APEX software (Francart et al., 2008; Laneau et al., 2005). Auditory stimuli were presented to the right ear. Auditory processing procedure and tasks were translated from those used and described by Poelmans et al. (2011). All auditory processing task thresholds were estimated by means of a one-up, two-down adaptive staircase procedure which is designed to target a threshold corresponding to 70.7% correct responses (Levitt, 1971). Tasks were presented within a three-alternative forced-choice, 'odd-one-out', paradigm, meaning that in each trial three stimuli were presented requiring the participant to determine which sound differed from the others. An inter-stimulus interval of 350 ms was used. All tasks were terminated after eight reversals. The arithmetic mean of the last 4 reversals is used as the threshold. Each participant completed two threshold runs of each task. As the aim was to evaluate a subject's sensory capability through the use of threshold estimations, the best score of the two runs was selected (for a similar approach see Boets et al., 2006).

Frequency modulation (FM) detection. Participants were required to detect a 2 Hz sinusoidal frequency modulation of a 1 kHz carrier tone with varying modulation depth. The reference stimulus was a pure tone of 1 kHz.

Modulation depth decreased by a factor of 1.2 from 100 Hz to 11 Hz, from which modulation depth then decreased by a step size of 1 Hz. The length of both the reference and the target stimulus was 1000 ms including 50 ms cosine-gated onset and offset. The detection threshold was defined as the minimum depth of frequency deviation (in Hz) required to detect the modulation.

Sound rise time discrimination (RT). This task consisted of a speech-weighted noise with linear amplitude rise times. Rise times varied logarithmically between 15 ms and 699 ms in 50 steps. The total duration of the stimuli was fixed to 800 ms, including a linear fall time of 75 ms. A stimulus of 15 ms rise time was used as the reference stimulus for each trial. Discrimination thresholds were defined as the minimal difference in the rise time required to discriminate between the reference and target stimulus.

Intensity discrimination (ID). This task is identical to the FM and RT discrimination tasks in its presentation and procedure. Stimuli, of an 800 ms duration, consisting of a speech-weighted noise and a linear rise time and fall time of 75 ms were used. The stimulus of 70 dB SPL was the reference stimulus for each trial. Intensity varied linearly between 70 dB SPL and 80 dB SPL in 40 steps of 0.25 dB SPL each. Discrimination thresholds were defined as the minimal intensity difference (in dB SPL) required to discriminate between the reference and the target stimulus. Being a non-temporal task, the ID task was used as a control variable to correct for psychophysical task demands.

STATISTICAL ANALYSES

Statistical analyses were performed with SPSS 20.0 software (IBM Corp. 2011). Data of all variables were checked with Shapiro-Wilk's test for normality. The assumption of homogeneity of variance was assessed by Levene's Test for Equality of Variances. Differences between HR and LR groups were investigated based on a paired *t*-test. Bonferroni adjusted alpha levels for each planned comparison was utilized in an effort to avoid the likelihood of false positive conclusions. Bonferroni adjusted alpha levels were determined by dividing the standard alpha of 0.05 by the total number of comparisons per question. The null hypothesis was rejected in situations where the found *p*-value was less than the adjusted alpha.

Partial Pearson correlations were calculated in order to determine the relation between auditory tasks and PA as well as the relation between measures of MA and PA. Separate Bonferroni adjusted alpha levels for the auditory and PA comparisons and the planned MA and PA comparisons were constructed and reported below. Finally, group differences on MA and PA tasks were re-examined including PA and MA respectively as control variables.

RESULTS

LETTER KNOWLEDGE

Results of both the productive and receptive letter knowledge tasks are found in Table 2. Significant group differences, based on an Bonferroni adjusted alpha of 0.025, were not found for either measure, $t(23.489) = -1.807$; $p = 0.084$, and $t(56) = -1.555$; $p = 0.125$. However, further examination of these results showed the potential influence of a lack of variance within each measure due to ceiling effects. Exploration of the results revealed that 91% and 74% of participants produced one or fewer errors on the receptive and productive letter knowledge tasks.

PHONOLOGICAL SKILLS IN HIGH AND LOW FAMILY RISK CHILDREN

To answer the question if the high-risk group demonstrates a deficit in the phonological domain, group differences of three aspects of phonological processing are tested. Component scores were created for each sub-skill: PA, verbal short-term memory, and lexical retrieval (RAN). Z-scores for all RAN and verbal short-term memory tasks were created based on control group mean and standard deviation. The RAN component score (RANcomp) was the average of both object and colour naming z-scores. The verbal short-term memory component score (VSTMcomp) was the average of the number repetition and non-word repetition subtest z-scores. The phonological awareness component score (PAcomp) was created by averaging total scores for syllable (SB, 2SD, FSD, 3SD, SS), rhyme (RD, RP), and phoneme awareness sub-test scores (PB, IPI, MPI, FPI).

Independent sample *t*-tests were performed to determine differences between groups in measures on phonological skills and used Bonferroni adjusted alpha levels of .017 (.05/3). All scores were found to be normally distributed. High-risk children were found to perform significantly poorer than low-risk controls on the component score of PA. Yet RAN and verbal short-term memory were not found to be significant when Bonferroni adjusted alpha of 0.017 was utilized. All results of group comparison, along with group mean and standard deviation scores, for each component score can be found on Table 2.

To further understand performance differences on specific phonological sub-skills group differences across the various grain sizes of PA were examined. In order to approach a normal distribution the negatively skewed variables, rhyme and phoneme awareness, were logarithmically transformed after the scores had been reversed (Field, 2009). Results demonstrated that high-risk readers scored significantly poorer at all levels of phonological awareness (adjusted $\alpha = 0.017$). Results of the group comparisons can be found in Table 2.

AUDITORY TEMPORAL PROCESSING AND ITS RELATIONSHIP WITH PA

To evaluate the proposed auditory temporal processing deficit theory of dyslexia in a sample of high- and low-risk pre-reading children, the various grain sizes of PA in relation to measures of RT and FM were studied. Firstly, utilizing an unadjusted standard alpha of 0.05, group comparisons demonstrated that high-risk children scored significantly poorer than controls on measures of RT discrimination. Group differences were not found for FM-detection nor for the control ID task. Yet with the application of Bonferroni adjusted alpha of 0.017, group differences for RT did not remain significant.

To assess the relationships between subjects' phonological awareness and auditory processing skills, Pearson's correlation coefficients were calculated between the subjects' scores on measures of syllable awareness, rhyme awareness, phoneme awareness, and measures of slow-rate dynamic auditory processing. Partial correlations were conducted to control for effect of group, as well Bonferroni adjusted alpha levels of 0.008 (0.05/6) and 0.0017 (0.01/6) were used to account for multiple comparisons. No significant correlations between measures of phonological awareness and auditory temporal processing were found. Yet a relation between syllable awareness and the measure of RT was found to be approaching significance ($p < 0.05$) (see Table 3).

Table 2: Literacy and cognitive variables: descriptive statistics and independent *t*-tests results

	NR		DYS			
Measure	M	SD	M	SD	*t*	*p*
Letter Knowledge						
Receptive (WRAT-III)	14.8	0.5	14.0	2.1	-1.807	.084
Productive (WRAT-III)	13.5	2.2	12.3	3.4	-1.555	.125
Morphological awareness	21.7	3.8	18.4	4.4	-3.017	.004*
Phonological Measures						
RANcomp	0.0	0.9	-0.5	0.8	-2.268	.027
VSTMcomp	0.0	0.9	-0.5	0.8	-2.292	.026
PAcomp	0.3	0.6	-0.5	0.7	-4.925	< .001*
Syllable awareness	18.4	2.6	15.4	2.7	-4.143	< .001*
Rhyme awareness	8.6	1.7	6.9	2.3	3.359	.001*
Phoneme awareness	14.4	4.0	10.6	5.4	2.630	.011*
Auditory Temporal Processing						
RT (ms)	299.7	184.3	408.0	178.6	2.216	.031
FM (Hz)	10.9	4.6	11.1	5.9	.191	.849
ID (dB)	3.3	1.3	3.8	1.8	1.035	.307

Notes. * p-values were found to be less then Bonferroni adjusted alpha levels

Pre-reading MA's relationship with PA

As reported in Table 2, a significant group difference was found for the measure of morphological awareness ($\alpha = 0.05$). As poor MA of older dyslexic children is often attributed to their poor PA skills, relationships of MA and the various grain sizes of PA were examined. As reported in Table 3, Pearson correlations were performed to examine these relationships with Bonferroni adjusted alpha levels of 0.017 (0.05/3) and 0.003 (0.01/3) to account for multiple comparisons. MA was found to be significantly related to syllable awareness ($p < 0.003$)

Due to the theoretical influence of PA on the attainment of morphological awareness and the observed significant correlation of MA and syllable awareness, a series of ANCOVAs were run to determine the effect of group differences while controlling for these variables. After introducing PAcomp as a covariate no significant difference could be found of the measure of morphological awareness between groups, $F(1,55) = 3.171$, $p = .080$, partial $\eta^2 = .055$. Similarly, the inclusion of syllable awareness as a covariate removed any group difference on the MA task, $F(1,55) = 3.632$, $p = .062$, partial $\eta^2 = .062$.

To further understand the relationship of MA and PA at the pre-reading stage of development the reverse of the above ANCOVAs were preformed, with MA as the covariate. Results showed group differences remained for both PAcomp and syllable awareness scores while controlling for MA, $F(1,55) = 13.518$, $p = .001$, partial $\eta^2 = .197$ and $F(1,55) = 7.961$, $p = .007$, partial $\eta^2 = .126$.

Table 3: Partial correlations between measures of PA, MA and auditory processing, controlled for group membership

	Auditory Processing		
	RT	FM	MA
Syllable awareness	-.306^	-.161	.341^{oo}
Rhyme awareness	.058	.000	.131
Phonemic awareness	-.020	-.056	.143

Note: Level of significance was obtained after Bonferroni adjustment.
Auditory processing and PA: □ p < .008, □□ p < .0017, ^ p < 0.05
Morphological awareness (MA) and PA: ^{o} p < .017, ^{oo} p < .003.

Discussion

In a group of pre-reading children with a family risk of dyslexia, this study investigated how the phonological deficit is expressed at various grain sizes of PA and whether these grain sizes are related to measures of auditory temporal processing. Moreover, the study attempted to shed light on the pre-reading relationship of MA and PA. Studying this relationship in a pre-reading population allows disentangling the relationship of PA and MA from reading experience.

Phonological processing deficit

As we don't know yet which children will be classified as dyslexic later on, the design of the study relies on comparisons of children with a family risk for developing dyslexia. In addition, it was not possible to fully disentangle environmental and instructional factors, yet the groups were balanced for age, gender, IQ, socioeconomic status, parental education, and letter knowledge. Although we have evaluated an at-risk sample, results were in line with what would have been expected for a dyslexic sample. The three aspects of phonological processing, phonological awareness, verbal short-term memory, and lexical retrieval, were able to differentiate between pre-reading children with a family risk of dyslexia and low-risk children. These results are also consistent with similar research that revealed deficits in pre-reading children with a family risk of dyslexia (Elbro et al., 1998; Gallagher et al., 2000; Pennington and Lefty, 2001; Snowling, Gallagher & Firth, 2003). Yet, it is worth noting that the group differences on the factors RANcomp and VSTMcomp could not withstand Bonferroni correction for multiple testing. This was in line with the findings of the prospective studies of Boets et al. (2006) and Elbro et al. (1998), while others, though using a retrospective analysis of their population, could find significant differences on measures of verbal short-term memory and RAN (de Jong & van der Leij, 2003; Pennington & Lefly, 2001).

PA at various grain sizes

Phonological awareness is believed to progressively develop from larger grain size units of syllables through rhyme awareness to the smallest grain size of phoneme awareness. The progression to an explicit awareness of this smallest unit is thought to only manifest after explicit instruction (Ziegler & Goswami, 2005). As a result of this developmental sequence, we hypothesized that group differences would be prominent for the larger grain units of syllable and rhyme, while phonemic awareness was predicted to be still underdeveloped in both groups.

As predicted, significant group differences were found for both syllable and rhyme awareness, yet unexpectedly group differences were also found for phoneme awareness. Since phoneme awareness has been said to only manifest as a result of explicit instruction, the discovery of developed phoneme awareness is a reasonable finding in light of the large proportion of the sample achieving at ceiling level on the letter knowledge tasks. Such results suggest some level of formal or informal literacy instruction, or at least knowledge of the alphabet.

Since phonological awareness has been consistently demonstrated to be one of the best pre-school predictors of reading achievement, it is reasonable to assume from our findings that the family risk group will contain a larger proportion of future cases of dyslexia compared to the LR group.

Auditory temporal processing and its relation with PA

We examined RT discrimination and FM detection in order to investigate slow-rate auditory temporal processing. We hypothesized that our findings would be in line with the slow-rate auditory temporal processing theory, in that both FM and RT would differentiate between both groups, but not our non-temporal auditory ID task. However, a significant difference in auditory temporal processing between the HR and the LR group was only observed for the measure of RT discrimination and not for FM. As expected, no group difference was found for intensity discrimination, the task that was used to control for task demands during assessment.

Although group differences for FM measures have been observed in an adult population (Heath et al., 2006; Ramus et al., 2003; Witton et al., 1998; yet see, Law et al. 2014), our findings in a pre-reading sample supported the findings of Boets et al. (2006). Boets and colleagues proposed that the lack of significant group differences for the FM measures may be attributed to either the typically greater inter-individual variability in children or to a poorly defined clinical group which may have contained substantial overlap with the control group. Although both are plausible arguments, the contrasting findings of significant group difference of RT and the lack of difference of FM in the same sample require further explanation. We suggest two plausible hypotheses explaining these contrasting findings: (1) differences may have resulted from sensitivity differences between measures, yet more likely (2) differences in the specific characteristics of the auditory stimuli being used could be to blame. As discussed by Law et al. (2014) it is most likely that the inconsistency between RT and FM results can be linked to the fact that both tasks represent different aspects of the auditory information in the speech signal. While FM represents the fine structure of the speech waveform, RT represents amplitude aspects of the speech envelope. Supporting the conclusion of the adult study by Law et al. (2014), our pre-reading results suggest that the primary auditory dysfunction in dyslexics is not to be found in the processing of the fine structure of the speech wave form but more likely in the perception of slow-rate dynamic auditory cues related to the speech envelope, as measured by the RT task. Such findings reinforce previous studies in both child and adult populations (Fraser et al., 2010; Goswami et al., 2002; Law et al. 2014; Poelmans et al., 2011;Thomson et al., 2006).

In summary, our findings do not support a general deficit in slow-rate auditory processing of dyslexics; nevertheless, dyslexics may have a more specific slow-rate dynamic auditory processing deficit specific to the envelopes of the speech waveform.

Relation between auditory processing measures and PA

An analysis of the relation between auditory processing measures and the various grain sizes of PA were made. FM showed no significant correlations with any of the three PA measures; a trend towards a RT and syllable awareness relationship was observed. Theoretically the relationship between RT and syllable awareness is sensible, due to the characteristics of the RT task. As discussed earlier, the stimuli used in the RT tasks are designed to correspond to time windows related to speech envelope cues that are supra-segmental. These cues are thought to facilitate syllable segmentation of the acoustic-linguistic signal. Thus it is more reasonable to find correlations between a measure of RT and syllable awareness than a smaller grain size unit of PA.

Although our research design does not permit any conclusions related to the directionality of this relationship, a plausible prediction can be made. Hämäläinen et al. (2005) discussed that it is highly improbable that an individual's poor phonological awareness would be influential on the lower-level skills of rise time discrimination. Hence, this relationship either reflects the same underlying perceptual deficit, or the auditory processing ability's underlining the RT task has a causal role in the development of PA.

Pre-reading morphological awareness's relation with PA

We explored the pre-reading relation of MA and the various measures of PA. The deficit of MA observed in dyslexics is often treated as consequential to the dyslexic reader's poor reading experience that in itself is a consequence of their poor PA skills. In order to disentangle this relationship we evaluated these measures in a pre-reading population to remove the influence of reading experience.

It was hypothesized that MA would be related to PA prior to reading instruction. As a consequence we predicted that any observed deficit in PA in pre-readers would produce an observable group difference in MA between high- and low-risk children.

Correlational analysis demonstrated a relation between MA and the composite score of PA and syllable awareness. Group comparisons confirmed our hypothesis, demonstrating that prior to any reading experience children at risk of dyslexia have a relative deficit in MA. To help further our understanding of this relationship, group differences of MA and PA were re-examined including PA and MA respectively as a control variable. After controlling for PA, group differences for the MA task were no longer present while group differences of PA were preserved when MA was added as a co-variant.

Our results support the research findings by Cunningham and Carroll (2013) and Carlisle and Nomanbhoy (1993) who reported a relation between pre-reading PA and later MA in that pre-reading PA predicted later MA. Our study differed in the sense that MA was assessed prior to the onset of formal reading instruction which allowed for disentangling reading experience from this relationship. As a result, we can conclude that PA is a relevant component of MA, independent of reading experience. Therefore the poor PA of dyslexic children, independent of reading experience, may be attributed to the observed MA deficit in dyslexic readers.

This study has demonstrated that children with a family risk of dyslexia possess reduced MA skills when compared to controls. As MA has been shown to be an important variable in predicting later word reading and reading comprehension, then a disruption or delay in MA development could potentially exacerbate later reading problems of children with dyslexia.

Although studies on adults and the results of this study have demonstrated MA deficits in individuals with dyslexia, evidence from intervention studies have demonstrated that direct instruction of MA does have a beneficial influence on bridging the MA achievement gap of dyslexic children (for a review see Bowers, Kirby and Deacon, 2010). This suggests that although early MA development is influenced by the child's phonological deficit, direct instruction and the development of a more explicit knowledge of the morphological structure of language has the potential to overcome this influence. In addition, several studies have suggested MA as a potential compensatory variable to overcome the phonological deficit and aid in reading achievement (Elbro & Arnbak, 1996; Law, Wouters, & Ghesquière, 2015; Leikin & Zur Hagit, 2006). For MA to be considered as a means of compensation, Law et al. (2015) noted two conditions which must be satisfied: MA must be found to be independent of PA, as well as MA being intact and a strength for individuals with dyslexia. Yet according to the findings of this paper neither of these conditions are capable of being met within a pre-reading population. If these conditions were to be met to support the findings of Law et al. (2015) the observed pre-reading influence of PA would need to diminish throughout development. A possible scenario could be that through literacy instruction a more explicit form of MA develops coupled with the development of orthographic representations of the morphemes. Such explicit awareness and representations could result in a new developmental trajectory independent of PA. Further longitudinal research spanning the pre- and post-reading instructional phases of development is required to fully understand the influence that direct literacy instruction has on the developmental trajectory of MA.

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CHAPTER 5

Predicting future reading problems based on pre-reading auditory processing and speech perception skills[4]

Developmental dyslexia is characterized by persistent reading and spelling difficulties. It has been well established that one of the major causes of these literacy problems lays in a deficit involving the quality and accuracy of phonological representations. Frequently these phonological problems have been linked to more basic perceptual impairments, specifically deficits in auditory temporal processing and speech perception. Yet, debates persist regarding the directionality and role of these relationships within the expressed reading deficits. Longitudinal studies of pre-reading children through literacy development could help to clarify these issues. The current longitudinal study followed 43 pre-reading children with and without a family risk of dyslexia through different stages of reading development. Results show atypical performance in auditory processing of rise time (RT) discrimination and phonological awareness (PA) at three time points (kindergarten, first, and second grade) in children who developed dyslexia. RT and frequency modulation (FM) sensitivity in kindergarten uniquely contributed to growth in reading ability in grades one and two, even after controlling for letter knowledge and phonological awareness. Highly significant concurrent and predictive correlations, even when controlled for autoregressive effects, suggest a potential causal relationship between auditory processing of RT and PA, with kindergarten RT significantly predicting later PA.

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INTRODUCTION

Dyslexia is a hereditary neurodevelopmental disorder characterised by persistent, lifelong reading and/or spelling impairments that cannot be accounted for by low intelligence or environmental factors (Vellutino, Fletcher, Snowling, & Scanlon, 2004). Recent etiological views of dyslexia have proposed a multi cognitive deficit model explaining the behaviour traits associated with dyslexia (Pennington, 2006). It is theorized that multiple genetic or environmental factors act probabilistically as risk or protective factors. It is these interactions that increase or decrease the probability of the development of the expressed behavioural symptoms attributed to dyslexia. One prominent etiological risk factor thought to be at the core of dyslexia, and found across all languages, is a deficit in the formation of, and/or access to, phonological representations (Snowling, 2000, but see Ramus and Szenkovits (2008)). As phonological skills have been shown to be vital in later literacy achievement, a disruption in the formation or low quality of phonological representations have negative consequences for literacy outcomes. For instance, pre-reading phonological awareness (PA) has shown to account for 40-60% of the later reading achievement of kindergarten children (Bryant, MacLean, Bradley, & Crossland, 1990; Caravolas, Hulme, & Snowling, 2001; Torgesen, Wagner, & Rashotte, 1994). Phonological awareness, which is the ability to recognize, isolate and manipulate basic speech units, develops early in life, prior to reading instruction. It is believed that the awareness of larger segmental units of words such as syllables, onsets and rimes develop first, while awareness of smaller units, referred to as phonemic awareness, is thought to develop only after print exposure (Goswami, 2002). The past few decades of research have shown evidence supporting theories that suggest a more primary sensory deficit in auditory processing could be responsible for the observed phonological deficits which underlie dyslexia (Boets, Ghesquière, Van Wieringen, & Wouters, 2007; Goswami, 2011; Tallal, 2004). Generally, the proposed theories suggest that the underlying cause of phonological difficulty stems from a deviant perception of specific temporal and dynamic auditory cues commonly represented in speech. High-level perceptual units, such as words, sentences and utterances, are an assemblage of smaller acoustic-phonetic cues that correspond to a time scale, specific to various phonological grain size units. For example, time windows of 0.14-0.33 sec correspond to segmental information relating to syllable recognition, while phoneme identification is relying on the perception of shortened time scales of 0.02-0.08 sec (Obrig, Rossi, Telkemeyer, & Wartenburger, 2010). It is thought that during the pre-literate phase of development, a deficit in the perception and processing of speech-specific acoustic cues could ultimately limit a person's ability to isolate and reflect upon basal phonological information, resulting in inaccurate phonological representations (Boets et al., 2007; Nittrouer, 2006). This cascading disruption in auditory processing through speech to the development of phonological representations has come to be known as the auditory temporal processing deficit theory.

Behavioural studies of individuals with dyslexia have provided support for the dynamic auditory processing theory, demonstrating deficits in auditory temporal processing (Goswami et al., 2002; Law, Vandermosten, Ghesquiere, & Wouters, 2014; Poelmans et al., 2011; Witton, Stein, Stoodley, Rosner, & Talcott, 2002) and speech perception tasks (Boets et al., 2011; Vandermosten et al., 2010). Additionally, studies have demonstrated a relationship between measures of auditory processing, phonology and literacy achievement in pre-school (e.g. Boets et al. (2011)), school-aged children (Poelmans et al., 2011; Talcott et al., 1999; Witton et al., 2002) as well as adults (Hämäläinen, Leppänen, Torppa, Müller, & Lyytinen, 2005; Law et al., 2014). For instance, in a 2002 study, Goswami et al. demonstrated that rise time (RT) sensitivity uniquely predicted 25% of the variance in reading and spelling in children, even after controlling for IQ.

Though theoretically appealing, the auditory deficit theory has faced growing criticism as others have not been able to replicate support for the dynamic auditory processing theory (Halliday & Bishop, 2006; Stoodley, Hill, Stein, & Bishop, 2006; White et al., 2006). For instance, criticism has arisen concerning the use of adequate controls for the psychophysical tasks, in that the observed poor performance of individuals with dyslexia in psychophysical studies may be a function of a general difficulty with task completion, thus resulting in the misinterpretation of non-sensory difficulties, such as those with attention or general task difficulty, as sensory ones (Roach, Edwards, & Hogben, 2004; Stuart, McAnally, & Castles, 2001). As seen in the study of Poelmans et al. (2011) one potential measure that is well suited to provide adequate control is a measure of intensity discrimination (ID). Group differences between typical and dyslexic readers are often not found in measures of ID (see Hämäläinen, Salminen, and Leppänen (2013)). As tasks of auditory processing and measures of ID were equal in design and methodology and group differences were not found, Poelmans et al. ruled out related task demands, attention, and cognitive aspects as driving factors of observed auditory problems.

Additionally, criticism has been drawn regarding the directionality and causality of the proposed theory. Arguments have been put forth stating that the processing of basic auditory stimuli may be affected in a top-down manner through poorly specified phonemic representations and are a consequence of the poor reading experiences (Bishop, Hardiman, & Barry, 2012). Evidence to support such a top-down relationship has been provided by two studies, suggesting that the auditory system gets tuned into listening for particular frequency and/or amplitude changes, thus creating a situation where an individual favors the processing of speech-specific auditory cues (Mayo, Scobbie, Hewlett, & Waters, 2003; Nittrouer & Miller, 1997). For instance, both studies have demonstrated that mature cue weighting strategies for speech develop in childhood as a result of increasing phonological awareness. Yet, a study by Johnson, Pennington, Lee, and Boada (2009) noted evidence of a bidirectional relationship of phonological awareness and auditory processing. As most studies have centered on a single time point and populations of adults and school aged children after the onset of literacy instruction (for a review see Hämäläinen, Salminen, & Leppanen 2013), questions of directionality and causality are difficult to address. Of the few studies which investigated pre-reading children longitudinally and could provide evidence of directionality, only one study, by Boets et al. (2011), examined both measures of auditory processing and speech perception. Boets et al. (2011) retrospectively explored the temporal auditory deficit theory in a population of pre-reading children who later developed dyslexia. They demonstrated atypical pre-reading slow-rate FM sensitivity and speech perception prior to reading instruction. These pre-reading measures were also found to relate to each other and uniquely predicted later growth in reading. Yet partial cross-lagged correlations prevented any reliable interpretation of directionality, leading Boets and colleagues to conclude a probable bidirectional relationship between auditory processing, speech perception and phonological awareness. Although measures across all levels were included in their study, auditory processing assessment did not concern speech envelope cues (such as RT discrimination) which recently have been shown to be one of the most sensitive measures in discriminating between dyslexia and controls (for a review see Hämäläinen, Salminen, & Leppänen 2013).

RT discrimination tasks, a measure of auditory processing, measure the larger grain size of the speech waveform, which are directly related to the speech envelope (Rosen, 1992). The perception of subtle differences in the rate of change in an amplitude envelope is vital for the segmentation of the speech signal into its base parts, thus aiding in the perception of speech (Goswami, Gerson, & Astruc, 2010). The inclusion of such auditory processing measures concerning speech envelope cues in a longitudinal study similar to that of Boets et al. (2011) could potentially offer greater insight into directionality.

Lastly, the auditory temporal processing deficit has received criticism relating to the lack of a clear association between speech perception tasks and auditory processing deficits in the literature calling into question the viability of the theory (Rosen, 2003). Although studies have demonstrated deficits independently in the slow-rate dynamic processing and speech-in-noise perception in individuals with dyslexia, only a handful of studies have assessed measures of both in the same population (Boets et al., 2011; Law et al., 2014; Poelmans et al., 2011). Poelmans et al. (2011) followed up the same population of Boets and colleagues in 6th grade. Although a relationship among slow-rate dynamic auditory processing (measures of RT and FM discrimination) and speech perception was present at an earlier age (Boets et al., 2011), Poelmans et al. found no clear evidence supporting a relationship at a later age. Additionally, using similar measures, Law et al. (2014) was also unable to support such a relationship in an adult population. Such results suggest that the observed auditory processing problems and their association with speech perception skills in individuals with dyslexia are present at birth through early childhood, thus contributing to early phonological deficits (Corriveau, Goswami, & Thomson, 2010). However, auditory processing problems may diminish through development and eventually become resolved. The diminishing of the severity of the auditory impairment and its association with speech perception through time may obscure potential effects of this deficit on later reading achievement and related skills (Galaburda, LoTurco, Ramus, Fitch, & Rosen, 2006). Thus, replication of Boets et al., (2011) findings and support for the existence of a pre-reading relationship of these variables is still needed to fully understand the relationship of auditory processing and speech perception early in development.

The aim of the current longitudinal study was to address the above criticism of the temporal auditory deficit theory while attempting to replicate earlier findings in an English speaking, pre-reading population. In addition to the FM detection task used in Boets et al. (2011), the more sensitive measure of RT was added as an assessment of speech envelope cues and to reflect the growing body of evidence of the importance of such cues in the early development of phonological awareness (Corriveau et al., 2010). Similar to Poelmans et al. (2012) an ID task was included within the testing battery to act as a means of control for attention difficulties and task related demands.

The objectives of this paper are threefold. First, to determine the relation between the kindergarten measures of auditory processing and speech perception tasks, and the cognitive and literacy outcome measures at grades 1 and 2. Secondly, to ascertain whether pre-reading RT discrimination, FM sensitivity and PA reliably predict later literacy achievement. Lastly, to investigate the presence of performance differences between groups based on the behaviourally observed literacy problems across three time points: pre-reading kindergarten, grade one and grade two.

Methods

Participants

Fifty-eight preschool children ranging in age from 4 to 5 years old and attending Senior Kindergarten (SK) in the Ontario, Canada public school system were originally selected for the study. At the completion of the third year of the study, 44 children remained. Three children were absent due to relocation to a school district not included in the study and one child's parents chose not to participate in the second phase of data collection. Additionally, to reduce the influence of second language learning on the sample, ten children were removed from the study after enrolling in a French immersion education program at their school. Children were initially recruited to meet one of two classifications, either being at high-risk (HR) for developing dyslexia, or being at low risk (LR). The high-risk group was selected based on the child having at least one first-degree family relative with an official diagnosis of dyslexia. The low-risk group consisted of children with no family history of reading difficulties. Groups were matched on measures of intelligence, socioeconomic status, gender, age, hyperactivity and educational environment. All participants possessed no signs of brain damage or long term auditory or visual impairments and were native English speakers.

Participation was voluntary. Upon registering parents completed an online questionnaire which informed the study of the child's medical history, behaviour and family history of reading and spelling (dis)abilities. The parental questionnaire also included screening for potential hyperactivity or behaviour problems, using questions taken from the Strengths and Difficulties Questionnaire (SDQ) (Goodman, 2001). Additionally, parental educational levels were measured using the seven point ISCED-scale (Unesco, 1997). Groups were found not to differ on measures of age, IQ, SES and parental educational level, as can be seen in table 1.

Table 1: Participant characteristics

	NR (n=23)	DYS (n=21)	*p*-value
Gender (F/M)	10/13	10/11	.783[b]
Age in months (mean ± SD)	64.0 ±4.2	62.1±2.8	.078[c]
Non-Verbal IQ[a] (mean ± SD)	109 ± 6.7	107 ± 6.3	.212[c]
Hyperactivity (mean ± SD)	2.7 ± 1.7	3.2 ± 2.3	.461[c]
SES (ISCED) (low/middle/high)	1/13/9	2/12/7	.900[d]
Mother's education (SE/PSE/GS)	3/15/5	4/14/3	.823[d]
Father's education (SE/PSE/GS)	5/13/5	5/13/3	.839[d]

Notes: [a] Scores are standardized (*M* = 100, *SD* = 15). [b] Pearson Chi-Square. [C] Independent *t*-test . [d] Fisher's Exact Test. SE = secondary school education, PSE = post-secondary education, GS= graduate studies

MATERIALS AND PROCEDURES

Socio-economic status (SES)

SES was assessed through the World Health Organization's (WHO) Family Affluence Scale II (FAS II). The FAS II is a four-part measure of family wealth scored as a composite measure ranging from 0-9. Similarly to Boyce, Torsheim, Currie, and Zambon (2006) initial scores were transformed into 3 categories of low affluence (0-2), middle affluence (3-5) and high affluence (6-9).

Intelligence (IQ)

The *Coloured Progressive Matrices* (Raven, 1998) was utilized to assess the non-verbal intelligence of each child in kindergarten. The test consists of 36 items in 3 sets measuring the spatial reasoning of participants. Each set within the test is arranged to measure the child's basic cognitive processes.

Literacy tests

Letter knowledge of the kindergarten group, including both receptive and productive letter knowledge, was assessed through the letter writing and naming subtests of the *Wide Range Achievement Test* (WRAT3) (Snelbaker, Wilkinson, Robertson, & Glutting, 2001). For each test the 15 most frequently occurring letters in English language books for children were used. For first and second grade assessment, spelling, word reading and non-word reading were measured with the corresponding subtests from the Woodcock-Johnson III (Woodcock, McGrew, & Mather, 2001). All subtest scores were normalized using provided grade based norms.

Phonological awareness (PA)

A subtest of the Clinical Evaluation of Language Fundamentals 4th ed. (CELF-4) (Semel, Wiig, & Secord, 2003) was selected to assess each participant's phonological awareness ability at various grain size levels. The subtest contains 11 elements: syllable blending (SB), 3 syllable deletion tasks (SD), syllable segmentation (SS), rhyme detection (RD), rhyme production (RP), phoneme blending (PB), initial phoneme identification (IPI), medial phoneme identification (MPI), final phoneme identification (FPI). As the ceiling was reached on both rhyme tasks across all grade level, both rhyme tasks were excluded from the creation of the PA variable. Similarly, syllable blending and 2 syllable deletion tasks were excluded from the calculation of PA for first and second grade students due to a high proportion of control subjects reaching ceiling level.

Verbal short-term memory (VSTM)

For all grades, two types of lists were used to assess VSTM. The first was *The Number Repetition Subtest* from The Clinical Evaluation of Language Fundamentals 4th ed. (CELF-4) (Semel et al., 2003), which required the immediate serial recall of orally presented series of digits with lengths of 2 to 9 digits. The test score equalled the total number of correctly recalled lists.

The second test was *The Nonword Repetition Test* from the Phonological Assessment Battery (PhAB) (Frederickson, Frith, & Reason, 1997) was utilized. This task required the children to repeat sequences of single syllable nonsense words that were presented orally. Sequence range progressively increased in length from 2 to 6. Each participant was requested to repeat the sequence in the correct order. A maximum score of 36 could be achieved for this test.

Lexical retrieval

Two naming tasks were administered in kindergarten and first grade to investigate lexical access. First was the *Colour Naming Test* from Boets et al. (2007). This test comprised five colours (black, yellow, red, green and blue) presented in a random order on a single sheet of paper arranged in 5 columns of 10 colour stimuli each. In addition, the *Object Naming Subtest* of the Phonological Assessment Battery (PhAB) (Frederickson et al., 1997) was used. Presented in a similar pattern as the colour naming task, the object naming subtest utilized five line drawings of common objects (desk, ball, door, hat, box). In second grade, letter and number naming tasks were included in the battery. All tests required the children to consecutively name the stimuli on a card as accurate and as quickly as possible. The number of correctly named items, per second, determined the score.

Auditory processing tasks

All auditory tasks were conducted at the child's school and administered individually in a private room, free from distraction. All auditory tasks were controlled by APEX software (Francart, Van Wieringen, & Wouters, 2008; Laneau, Boets, Moonen, Van Wieringen, & Wouters, 2005) on a Dell Latitude D510 computer. Auditory stimuli were presented through Sennheiser HDA 200 headphones to the right ear. All auditory processing task thresholds were estimated by means of a one-up, two-down adaptive staircase procedure which is designed to target a threshold corresponding to 70.7% correct responses (Levitt, 1971). Similar to Poelmans et al. (2011), all tasks were presented within a three-alternative forced-choice, 'odd-one-out', paradigm. Thus, in each trial the child was required to determine which of the three presented stimuli sounds different from the others. An inter-stimulus interval of 350 ms was used. All tasks were terminated after eight reversals. The arithmetic mean of the last 4 reversals was used as the threshold for each task. Each participant completed two threshold runs of each task. The best of these two runs was used as their threshold score.

Auditory temporal processing. Two psychophysical threshold tests were used to assess auditory temporal processing. In the frequency modulation (FM) detection test, participants were required to detect a 2 Hz sinusoidal frequency modulation of a 1 kHz carrier tone with varying modulation depth. Modulation depth decreased by a factor of 1.2 from 100 Hz to 11 Hz. At this point modulation depth decreases by a step size of 1 Hz. The detection threshold was defined as the minimum depth of frequency deviation (in Hz) required to detect the modulation. In the sound RT discrimination task, participants had to detect differences between a fixed reference stimuli and the target. Target stimuli consisted of amplitude RTs that varied logarithmically between 15 ms and 699 ms in 50 steps. Discrimination thresholds were defined as the minimal difference in the RT required to discriminate between the reference and target stimulus.

A non-temporal task, intensity discrimination (ID), was used as a control variable to correct for psychophysical task demands. The ID task was identical to the FM and RT discrimination tasks in its presentation and procedure. Participants were required to detect differences in intensity between a reference stimulus of 70 dB SPL and a target which varied linearly between 70 dB SPL and 80 dB SPL in 40 steps of 0.25 dB SPL each. Discrimination thresholds were defined as the minimal intensity difference (in dB SPL) required to discriminate between the reference and the target stimulus. A more detailed description of the stimuli can be found in Law et al. (2016).

Speech-in-noise perception test. Words in noise perception was assessed with The Computer Aided Speech Perception Assessment (CASPA) developed by Boothroyd (2006) (for application see McCreery et al. (2010)). A random selection of 3 lists of 10 CVC words were presented using the recording of a female speaker with a competing speech weighted noise at varying signal-to-noise ratios (SNR) (0 dB, -5 dB, and -10 dB). Each list contained a single occurrence of the same set of 30 phonemes (20 consonants and 10 vowels). A practice list of 0 dB SNR was first administered to the participant. Participants were instructed to repeat each target word or perceived phoneme after presentation. The percentage of correctly perceived phonemes were calculated for each SNR. The Speech Reception Threshold (SRT) was calculated for each participant through fitting to the data as a logistic function relating the percentage of correct responses to SNR level (for a similar approach see Poelmans et al. 2011). Final values for each measure were inverted by multiplying by a factor of -1 to obtain a positive correlation matrix.

STATISTICAL ANALYSES

Statistical analyses were performed with SPSS 20.0 software (IBM Corp. 2011). Data from all variables were checked with Shapiro-Wilk's test for normality. All data were found to be normally distributed ($p > 0.05$) with the exception of some auditory processing data: FM and RT in kindergarten in addition to FM at both first and second grades as well as ID at first grade. In order to approach a normal distribution, variables were transformed by a logarithmic transformation. The assumption of homogeneity of variance was assessed by Levene's Test for Equality of Variances. Group comparisons were investigated based on an independent-samples *t*-test. Correction for multiple testing was applied across all group comparisons to avoid the likelihood of false positive conclusions through the application of the False Discovery Rate (FDR) procedure (Benjamini & Hochberg, 1995). The FDR procedure is a simple sequential Bonferroni-type procedure that has been demonstrated to control for the false discovery rate for independent test statistics.

RESULTS

RELATIONSHIP BETWEEN EARLY LITERACY, PHONOLOGICAL AWARENESS, AUDITORY PROCESSING AND SPEECH-IN-NOISE PERCEPTION.

Table 2 shows concurrent and predictive relationships between all measures of dynamic auditory processing, speech in noise perception, phonological awareness and measures of literacy. To obtain a positive correlation matrix both measures of auditory processing were multiplied by -1.

Of the two kindergarten dynamic auditory processing measures only RT correlated significantly with PA and the reading composite scores at all grade levels. Additionally, RT in first grade was found to be significantly correlated with PA, while it was found to be approaching significance with reading at grade 1 and 2. However speech in noise was not found to relate to any of the assessed measures across all time points. As what would be expected from the auditory processing deficit theory both measures of auditory processing (RT & FM) were found to be significantly correlated within and between each grade level. However auditory processing measures were not found to be related at any time point with measures of speech in noise.

All significant correlations as depicted in table 2 maintained significance when group was introduced as a control variable with the exception of the relationship of kindergarten and grade one RT with grade 1 PA (RT-Kindergarten – PA in grade 1, $r = 0.136$, $p = 0.391$; RT-G1 – PA in grade 1, $r = 0.033$, $p = 0.835$), as well as the relationship of letter knowledge with kindergarten RT ($r = 0.071$, $p = 0.653$), and grade 2 reading ($r = 0.261$, $p = 0.095$) and PA ($r = 0.289$, $p = 0.064$). Additionally, partial correlations controlling for IQ resulted in the same pattern of findings displayed in table 2.

Similar to Boets et al. (2011) directional effects of auditory processing were investigated through a series of cross-lagged partial correlations while controlling for autoregressive effects. Figure 1 displays concurrent, autoregressive and cross-lagged (partial) correlations. RT and PA in kindergarten and first grade were found to have a significant concurrent relationship. Significant predictive relationships of RT in kindergarten with first grade RT and PA measures were found and are depicted in figure 1a. After controlling for autoregressive effects of kindergarten PA the predictive relationship of kindergarten RT and first grade PA was maintained, thus suggesting directionality. FM was not found to have significant concurrent and predictive relationships with PA across all grades. The lack of significance of the cross-lagged partial correlations indicated the lack of directional support for relationships of FM sensitivity and later PA.

Predicting later literacy achievement by pre-reading RT discrimination, FM sensitivity and Phonological awareness.

In order to assess the predictive factors relating to first and second grade literacy measures (reading and spelling), four sets of simultaneous linear regression analyses were calculated. For each model later literacy performance in grade one and two were predicted by kindergarten measures of phonological awareness (PA), letter knowledge (LK), and both measures of dynamic auditory processing (RT and FM). Results of the regression analysis are shown in table 3.

Results revealed that phonological awareness, RT discrimination and FM sensitivity uniquely contributed to reading at both first and second grade. At both time points no significant contribution was found of letter knowledge for reading or spelling. RT was found to contribute the most to reading. For first grade reading RT accounted for 13.3% of the variance while PA and FM were found to explain 12.1% and 6% of the variance, respectively. In the case of second grade reading, RT accounted for 14.1% of the variance, in addition to the 13.5% and 6.3% of the variance attributed to PA and FM sensitivity threshold. Linear regression of first grade spelling did not reveal the same predictive factors, as PA in kindergarten was found to be the only contributing variable explaining 17% of the variance. PA, RT and FM were found to contribute to the second grade spelling. PA accounted for 10% of the variance; while RT and FM were found to account for 8% and 6.3% of the variance of second grade spelling.

Table 2: Pearson correlations between kindergarten measures of auditory processing and speech perception tasks and cognitive measures at grades 1 and 2.

	Kindergarten				Grade1						Grade 2		
Measure	2	3	4	5	6	7	8	9	10	11	12	13	14
Kindergarten													
1. RT(ms)	.531***	.201	.286	.024	.580***	.414**	.094	.443**	.369*	.175	.391**	.387**	.264^
2. FM(Hz)		.023	.254^	.028	.462**	.507***	.065	.211	.043	.057	.136	.042	.045
3. SPIN			.002	.282^	.219	.214	.252	.055	.047	.098	.118	.052	.016
4. PA				.519***	.251	.320*	.074	.602***	.604***	.626***	.672***	.615***	.583***
5. LK					.098	.124	.078	.298*	.417**	.507***	.372*	.403**	.521***
Grade 1													
6. RT(ms)						.739***	.100	.413**	.328*	.071	.373*	.332*	.204
7. FM(Hz)							.296^	.464**	.385**	.245	.440**	.372*	.227
8. SPIN								.006	.031	.107	.174	.018	.025
9. PA									.709***	.683***	.798***	.716***	.629***
10. Reading										.707***	.867***	.988***	.871***
11. Spelling											.716***	.711***	.719***
Grade 2													
12. PA												.863***	.767***
13. Reading													.864***
14. Spelling													

Note. ^p < .10. *p < .05. **p < .01. ***p < .001.

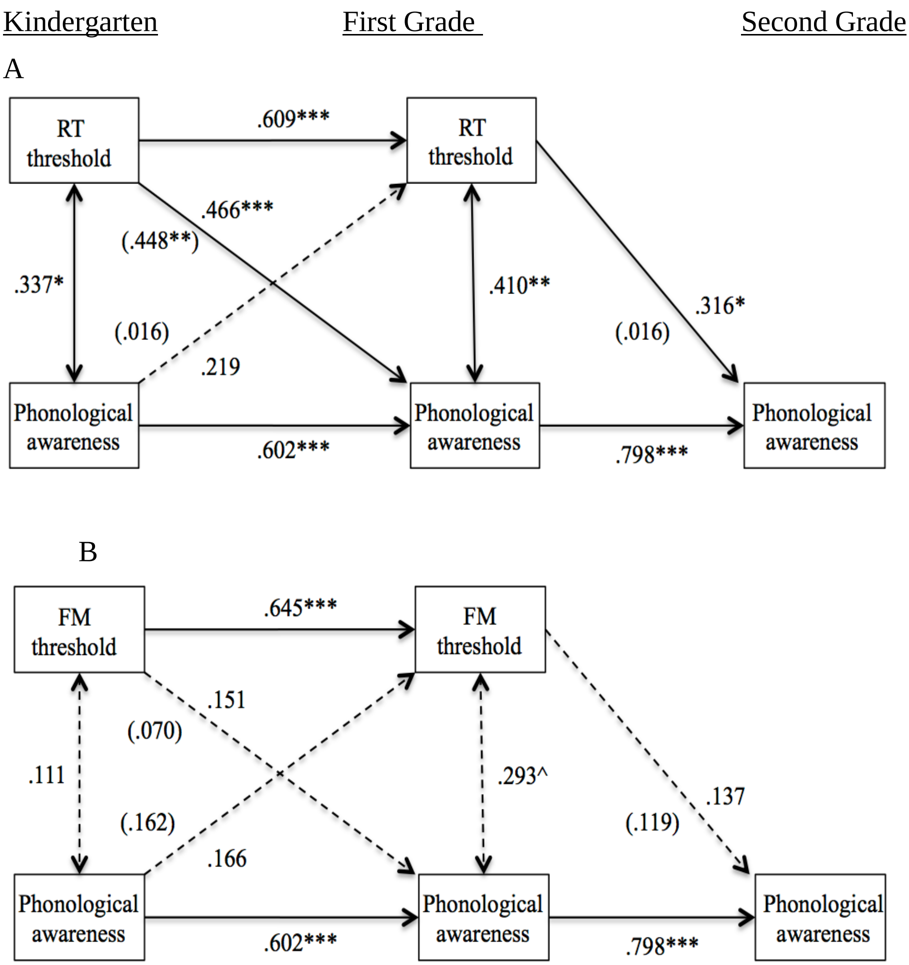

Figure 1. (A) Cross-lagged (partial) correlations modeling the relations between RT discrimination and phonological awareness across all time points. (B) Cross-lagged (partial) correlations modeling the relations between FM sensitivity and phonological awareness across all time points. Partial correlations corrected for autoregressive effect are presented in parentheses. ^p < .10. **p* < .05. ***p* < .01. ****p* < .001.

Table 3: Unique variance in first and second grade reading, and spelling accounted for by Letter knowledge (LK), Phonological awareness (PA), Rise time (RT) and Frequency (FM) (R^2change and standardized Beta)

	First Grade				Second Grade			
	Reading		Spelling		Reading		Spelling	
Measures	R^2 change	β	R^2 change	β	R^2 change	β	R^2 change	β
PA	.121	.439**	.170	.521**	.135	.464**	.100	.398**
LK	.009	.118	.015	.152	.005	.088	.042	.249
RT	.133	.439**	.029	.206	.141	.453**	.080	.341*
FM	.060	.287*	.022	.173	.063	.294*	.063	.293*
Total R^2	.529		.479		.549		.527	

Note: *$p < .05$. **$p < .01$. ***$p < .001$.

Performance of children with dyslexia versus non-literacy impaired readers

To investigate the presence of performance differences between groups based on the behaviourally observed literacy problems, the sample was retrospectively divided. Two groups, children with dyslexia and unimpaired children, were created based on their performance on literacy tasks at the start of second grade. A classification of literacy impairment was based on a child performing below the 10^{th} percentile on two of the three second grade literacy measures: word reading, spelling or non-word reading. The resulting dyslexic (Dys) group consisted of 17 high-risk children and 4 low-risk children. The literacy unimpaired (control) sample was constructed of 19 low risk children. Four children from the high-risk group did not meet the cut-off criteria of dyslexia. Past research has demonstrated that similar groups of high risk normal reading children differ across many measures from low risk controls, so it was decided to exclude these individuals from group analysis of control subjects (Pennington & Lefly, 2001; Snowling, Gallagher, & Frith, 2003). Additionally, due to the small sample size of high-risk normal reading children separate statistical analysis was not performed on these subjects.

Tables 4 to 6 show the performance of children on all auditory, speech perception, phonological and literacy tests according to their classification and age. Independent t-tests found no group differences across measures of age, gender, IQ, SES and hyperactivity ($p > 0.05$).

Literacy

Results of the literacy tasks are found for all grades in tables 4 to 6. Literacy in kindergarten was represented by a composite score formed by the averaging of z-scores of productive and receptive letter knowledge in kindergarten. Literacy in both first and second grade was measured by word reading, non-word reading and spelling. Due to the highly significant correlation between word reading and non-word reading measures (.825 and .859 in grade 1 and grade 2 respectively), a single reading score was created for each participant by averaging of z-scores of both tasks. Group comparisons, after the application of the FDR procedure revealed that dyslexic readers were found to perform significantly poorer than controls on all literacy measures in first and second grades. Group differences for letter knowledge were found to remain significant after the application of the FDR procedure.

PHONOLOGICAL SKILLS

Each domain of one's phonological skills, as represented in Wagner & Torgesen (1987), are reported in Tables 4-6 for each grade level. Phonological awareness was assessed at both syllable and phoneme level. Phonemic awareness was more heavily weighted in the construction of PA in first and second grade due to achieved ceiling effect on some syllable level tasks by controls which resulted in the removal of these tasks from the construction of PA. VSTM and RAN are reported as composite scores. Independent sample t-tests, utilizing the FDR procedure, revealed significant differences between groups across all measures and time points with the exception of VSTM and RAN in kindergarten and RAN in grade 2.

Table 4: Performances on literacy, cognitive, auditory processing and speech-in-noise perception tasks in kindergarten.

	Control		DYS			
Measure	M	SD	M	SD	t	p
Literacy						
Letter Knowledge^	0.3	0.3	-0.3	1.0	-2.444	.022*
Cognitive Measures						
RANcomp	0.3	1.1	-0.3	0.8	-2.227	.032
VSTMcomp	0.2	0.7	-0.3	0.9	-1.922	.062
PA	32.7	4.6	26.4	6.3	-3.535	.001*
Auditory Temporal Processing						
RT (ms)	218.0	196.5	348.0	212.0	-2.385	.022*
FM (Hz)	10.6	8.9	9.7	9.7	-0.720	.476
ID (dB)	3.2	1.3	3.7	1.5	1.072	.291
Speech-in-noise (SRT) (dB)	-7.6	1.0	-7.7	1.3	-0.292	.772

Notes. ^ failed Levene's test for Equality of Variance. * significant *p*-value after applying the FDR procedure to correct for multiple testing.

AUDITORY PROCESSING AND SPEECH PERCEPTION

As the aim of the auditory processing measures was to discover the threshold of the subject's sensory capability the best score of the two trials for each task was selected. Threshold means and standard deviations of all auditory stimuli at each grade level can be found in Tables 4-6. Group differences were not found for the control variable ID, thus assuring that group differences observed across the other auditory processing measures could not be attributed to task demands of the psychophysical tests and/or intensity-related processing.

Results demonstrated statistically significant poor performance of children with dyslexia on measures of RT discrimination at all three time points when a standard alpha of 0.05 was used: kindergarten ($t(38) = -2.385$; $p = 0.022$), first grade ($t(38) = -2.165$; $p = 0.037$) and second grade ($t(34.396) = -2.199$; $p = 0.035$). Yet the same could not be said for measures of speech perception, FM-detection nor ID. Although group differences were found for RT, significance was not maintained for RT at first and second grades after the application of the FDR procedure to correct for multiple testing.

Table 5: Performances on literacy, cognitive, auditory processing and speech-in-noise perception tasks in grade 1

	Control		DYS			
Measure	M	SD	M	SD	t	p
Literacy						
Reading	0.3	0.7	-2.2	0.9	-9.261	<.001*
Spelling	112.2	10.5	100.7	6.7	-4.175	<.001*
Cognitive Measures						
RANcomp	0.4	0.9	-0.3	0.7	-2.641	.012*
VSTMcomp	0.4	0.8	-0.4	0.8	-2.817	.008*
PA	33.9	5.2	23.5	7.9	-4.870	<.001*
Auditory Temporal Processing						
RT (ms)	94.0	59.5	150.0	122.0	-2.165	.037
FM (Hz)^	6.2	2.3	8.2	6.4	0.901	.374
ID (dB)	1.9	0.8	2.5	0.9	1.890	.066
Speech-in-noise (SRT) (dB)	-8.9	1.1	-8.9	1.7	0.125	.901

Notes. ^ failed Levene's test for Equality of Variance. * significant *p*-value after applying the FDR procedure to correct for multiple testing.

Table 6: Performances on literacy, cognitive, auditory processing and speech-in-noise perception tasks in Grade 2

	Control		DYS			
Measure	M	SD	M	SD	*t*	*p*
Literacy						
Reading	0.9	0.5	-0.8	0.5	-10.462	<.001*
Spelling	105.0	8.5	86.7	7.0	-7.471	<.001*
Cognitive Measures						
RANcomp	0.2	0.7	-0.1	0.7	-1.554	.128
VSTMcomp	0.3	0.6	-0.2	0.7	-2.661	.011*
PA	39.2	2.8	29.6	5.9	-6.451	<.001*
Auditory Temporal Processing						
RT(ms)^	73.0	46.5	125.0	136.5	-2.153	.035
FM (Hz)^	5.4	2.7	6.7	9.7	0.853	.399
ID (dB)	1.6	0.7	2.3	1.9	1.620	.113
Speech-in-noise (SRT) (dB)	-10.1	1.6	-10.0	1.8	0.198	.844

Notes. ^ failed Levene's test for Equality of Variance. * significant *p*-value after applying the FDR procedure to correct for multiple testing.

Discussion

The aim of this study was to investigate the auditory temporal processing deficit theory. This theory postulates that the primary deficit of dyslexia lays within poor auditory processing of speech specific auditory cues which cascades through speech perception disrupting the formation of quality phonological representations and ultimately impacting literacy achievement. In a longitudinal design this study sought to examine whether future literacy achievements or difficulties could be predicted based on pre-reading auditory processing and speech perception skills.

To achieve this end, a group of pre-reading children were followed from the start of kindergarten to second grade. Predictive relationships between pre-reading measures of auditory processing and emerging phonological and literacy skills were explored, while, group differences for auditory processing, speech perception and phonological measures were assessed based on the reading success or failure in second grade.

In line with previous research (Boets et al., 2011; Pennington & Lefly, 2001; Snowling et al., 2003), children classified as dyslexic in grade two were found to differ significantly on all measures of phonological awareness, and literacy, across all three time points, when compared with typically developing readers.

Theoretically, significant relations were expected between auditory processing and speech perception, but this wasn't the case. An examination of the relationships between these variables revealed no clear relationship at any time point measured. Therefore, this study could not support the theorized directional pathway from auditory processing through speech perception to phonological skills as proposed by the auditory temporal processing deficit theory. Similarly, the speech-in-noise measure was found not to be significantly related to measures of phonological awareness or literacy within each time point. Two possible arguments can be made to explain these findings. Firstly, it is possible that slow-rate auditory processing independently relates to reading and not via speech perception. As both measures of RT and FM detection utilize auditory cues commonly represented in the speech signal, this explanation is highly unlikely. An alternative explanation offered by Poelmans et al. (2011) theorized that the developmental link between auditory processing and speech perception might diminish with age due to the effect of different developmental influences over time. Thus, the inability to discover a relationship between these measures may be a result of the age at which these measures were assessed. Past research has demonstrated the existence of a relationship between early auditory processing and later speech perception in infancy (Leppänen et al., 2010). In addition, it is known that a new-born's auditory processing is sensitive to all phonemic contrasts and quickly becomes constrained to acoustic features specific to their native language (Kuhl, 2004). Given this, a study by Vanvooren et al. (2016) which found no link between auditory processing and speech perception in pre-reading children, suggested that auditory processing's influence on speech perception may be limited to the first year of life. Vanvooren et al. (2016) argued that impairment in the processing of speech specific auditory cues at this stage could potentially impede speech perception during early stages of language acquisition. At the age the children were assessed in this study, speech-in-noise perception not only relies on bottom-up auditory processing but also involves various top-down processes such as semantic and syntactic cues. Yet it is important to consider that these results reflect only one aspect of speech perception, that being speech-in-noise perception. Although this measure does represent a more natural measure of speech perception it must be noted that this task relies not only on basic acoustic perception but also elements of auditory attention or selective attention which may have influenced results.

Although RT discrimination and FM detection measures were not found to relate to the speech-in-noise measure, a significant relationship was found between these two pre-reading measures of auditory processing. In addition pre-reading RT was found to relate to concurrent and later phonological awareness and reading in grades one and two. The findings of a pre-literate relationship of measures of RT and phonological awareness are in line with other longitudinal studies that explored RT and early pre-reading phonological awareness (Corriveau et al., 2010). Pre-reading and first grade measures of FM were not found to relate to later phonological and literacy measures. The lack of pre-reading FM's relationship with phonological measures contradicted findings by Boets et al. (2011) who found pre-reading FM to correlate with measures of phonology across all grade levels. As the FM detection measure of this study closely mirrored that used by Boets et al., a potential explanation of the inconsistent results could rely on differences in the phonological awareness measures used. When compared with Boets et al. (2011) phonological awareness within this study was more heavily weighted by measures of phonemic awareness across all grades. This is a function of the testing battery used as well as a result of the achieved ceiling effect on some syllable level and rhyme production and identification tasks which resulted in their removal from the construction of PA, while Boets' et al. PA measure included both rhyme tasks in addition to a spoonerism task. The grain size level of the PA measure is of importance when considering its relations with speech specific auditory processing measures such as FM. As discussed earlier, time windows of 0.14-0.33 sec correspond to segmental information relating to syllable recognition, while phoneme identification is reliant on the perception of shortened time scales of 0.02-0.08 sec (Obrig et al.,2010). As the stimuli used within the FM task was based on a 2 Hz sinusoidal frequency modulation, it would be reasonable to expect a relation with a PA measure weighted by subtasks assessing grain size units at the rime and syllable level, as demonstrated in Boets et al. (2011).

Regression analyses of literacy measures accounting for letter knowledge and phonological awareness, FM sensitivity and RT discrimination demonstrated kindergarten FM and RT's ability to uniquely predicted growth in reading achievement at grades one and two. Contrary to

Boets et al. (2011), RT and FM were found to both uniquely predict variance in first and second grade reading suggesting that basic auditory processing skill's impact on reading development is not limited to the time point prior to reading instruction but extends through early stages of reading development.

Additionally, kindergarten measures of RT and FM each were found to predict 8% and 6.3% of the unique variance of second grade spelling once variance of kindergarten letter knowledge and PA were accounted for. Yet, both variables were found not to predict any variance in first grade spelling. A possible explanation of these differences across grades may be a result of differential strategies used in early and later spelling achievement. Word stimuli utilized in the grade one spelling assessment primarily consisted of simple, high frequency, single syllable words common in children's literature (e.g. hat, the, it, my, book). Therefore, children may have utilized direct recall strategies from long term memory instead of utilizing a phonetic strategy during the first grade assessment (Steffler, Varnhagen, Friesen, & Treiman, 1998). An automated direct recall strategy could have limited FM and RT influence through phonological awareness on first grade spelling outcomes. In contrast the second grade child progressed to larger, less frequently observed words in the spelling word list for second grade, requiring the application of more phonemic based spelling strategies.

These regression results support the findings of Boets et al. (2011) in that individual differences in auditory processing are not simply a consequence of phonological awareness and early literacy achievement. The unique predictive ability of these pre-reading measures highlight auditory processing's role in early reading development.

To address questions surrounding the directionality of the hypothesised causal pathway as predicted by the auditory temporal processing deficit theory, an investigation of the interrelations of measures of auditory processing and phonological awareness across time points was conducted. Significant concurrent and predictive relationships were observed between the auditory processing measure of RT discrimination, and phonological awareness. Partial cross-lagged correlations, controlling for autoregressive effects, confirmed the directionality between slow rate auditory processing (specific to RT discrimination) and phonological awareness. Results demonstrated a larger impact of RT performance on future PA development than PA's influence on auditory processing development. Thus supporting the bottom-up model proposed by Tallal (1980) within the first years of reading development. Similar to Boets et al. (2011) predictive relations between auditory processing, when measured through FM detection tasks, and phonological processing could not be interpreted in a directional way. These findings could be interpreted as a result of the phonological awareness measure with a higher proportion of phonemic awareness tasks, as was discussed earlier. Yet, as the lack of directionality between FM measures and phonological awareness was also found in Boets et al., we could argue that RT is less influenced by top-down processes during early stages of reading acquisition, and thus a more sensitive measure, when compared to FM, in establishing casual pathways as predicted by the theory.

As predicted by the auditory temporal deficit theory, group differences were expected across both measures of auditory temporal processing (RT and FM) but not for the non-temporal auditory ID control task. Group analyses demonstrated a statistically significant poorer performance of children later diagnosed with dyslexia on the measure of RT discrimination at the pre-reading phase, while a trend towards significance was observed for RT discrimination in first and second grade. Yet the same could not be said for measures of speech perception, FM-detection or ID. The finding of poorer performance of dyslexic children on RT discrimination tasks prior to formal reading instruction indicates these problems are not consequential of the expressed literacy problems characteristic of dyslexia. These results were in line with the bulk of previous studies across age groups and languages (for a review see Hämäläinen et al., 2013). The lack of significant group differences at each time point for the FM measure was unexpected as past research in both dyslexic children (Boets et al., 2011) and adults (Ramus et al., 2003; Witton et al., 2002) have demonstrated clear group differences. Similar to the results of this study, Law et al. (2014) unexpectedly reported a lack of group difference for FM in the presence of a RT-deficit. As stimuli within the FM task represent the fine structure of the speech waveform, while RT stimuli represent amplitude aspects of the speech envelope, Law et al., suggested that such a difference in findings between both temporal auditory measures may imply the existence of a specific deficit in the perception of slow-rate dynamic auditory cues related to the speech envelope.

While our results are not able to directly support the proposed auditory temporal deficit theory, results suggest that a slow-rate dynamic auditory processing deficit, confined to speech envelope cues rather than to fine structure, was found to uniquely predict later literacy achievement. Yet, RT's direct influence on literacy outcomes was limited and was found to be mostly mediated through phonological processing. These findings extend our power of predicting future literacy outcomes to developmentally earlier precursors. Corriveau et al. (2010) noted that such advances are vital to practitioners for early assessment and design of early intervention techniques for children at risk of reading failure prior to the entry of first grade.

The existence of speech-in-noise perception deficits and its mediating role in auditory processing and reading-related measures was not observed. Further research is needed in this area with attention to the selection of speech-in-noise masking stimuli that may not be as dependent on top-down cues. Additionally, to better understand the theoretical causal model proposed by the auditory temporal processing deficit theory, future research is required to replicate and extend these findings to earlier ages. Although measures of auditory processing were able to uniquely predict later reading outcomes, this proposed deficit model, along with most single cognitive deficit model of dyslexia are incapable of explaining all of the expressed behavioral traits observed in a dyslexic population. Additionally, this research along side other studies discussed throughout this paper have demonstrate that not all individuals with auditory processing or phonological impairments develop dyslexia. Such results lend support to the proposed multiple deficit model proposed by Pennington (2006) which stresses the need to explore a multifactorial aetiology which accounts for multiple risk or protective factors, It is thought that these risk and protective factors act probabilistically together to produce the expressed behavioral symptoms of dyslexia. Our results suggest that a multifactorial approach should be explored to fully identify the mechanisms underlying dyslexia. By investigating alternative cognitive factors, such as orthographic or morphological processing (Bekebrede, van der Leij, & Share, 2009), alternative perceptual factors (Stein, 2001) and biological explanations (Nicolson, Fawcett, & Dean, 2001), the variance and comorbid symptoms associated with the dyslexic population can be better understood.

Several limitations regarding this work are worth noting. First, the generalizability of the findings reported in this paper may be restricted due to the limited sample size of the study. Additionally, the restricted sample size limited the statistical analysis we performed. A larger sample size would have permitted the use of structural equation modeling to allow for an analysis of the causal paths of the model we were investigating. It could be argued that sampling bias may have occurred during the recruitment. As enrolment for the study relied on parental responses to flyers sent home with children and did not involve a general sample, it could be argued that educationally motivated parents or parents concerned about their child's literacy success may had been more inclined to respond. The avoidance of this potential sampling bias was not possible due to restrictions placed on the solicitation of parent involvement by the school administration.

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CHAPTER 6

Early development and predictors of morphological awareness: disentangling the impact of decoding skills and phonological awareness[5]

Morphological Awareness (MA) has been demonstrated to be influential in the reading outcomes of children and adults. Yet little is known regarding MA's early development. To better understand MA's growth and association with PA and reading, this longitudinal study reports on the development of MA in a group of pre-reading children with a family risk of dyslexia and age matched controls from kindergarten until grade 2. MA deficits were observed in the reading impaired group at all time points. PA was found to contribute to MA development prior to the onset of formal reading instruction after which decoding skills explained the majority of the variance. Findings are discussed in terms of current theories of MA development and educational implications.

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Introduction

Dyslexia, a lifelong neurodevelopmental disorder characterized by severe reading and/or spelling impairments (Vellutino, Fletcher, Snowling, & Scanlon, 2004), It has been well established in the literature that a major contributing variable of the expressed literacy problems lay within a deficit in the development of—or access to—phonological representations (Snowling, 2000; Tønnessen, 1997). Manifestations of this phonological deficit have been observed in, difficulties with the retention of information in the phonological loop of working memory, reduced speech in noise perception, poor lexical retrieval, and a reduced capacity to manipulate the phonemic structure of words (Wagner & Torgesen, 1987).

Over the past several decades, reading research has amassed an impressive body of evidence demonstrating the importance of phonological awareness (PA) in literacy achievement. PA's strong association with reading has been observed across various alphabetic languages and has been found to exist despite individual differences in age, vocabulary knowledge, reading experience, and IQ (Bradley & Bryant, 1983; Kirby, Parrila, & Pfeiffer, 2003; Melby-Lervåg, Lyster, & Hulme, 2012). As a group, dyslexic readers have been shown to perform more poorly then normal reading controls on a variety of measures involving the perception, manipulation, production and retrieval of phonological information (e.g. Melby-Lervåg, Lyster, & Hulme, 2012 and Snowling, & Stackhouse, 2013). Yet more recent theories of dyslexia have highlighted the existence of a multitude of interacting deficits. It is thought that individuals' expressed behavioral deficits may be a function of multiple cognitive factors acting as risk or protective factors, independently or in conjunction with the phonological deficit (Pennington, 2006).

Morphological Awareness (MA), the explicit awareness and ability to manipulate and reflect upon the morphemic structure of words, is one of the cognitive variables that could be viewed as a potential risk or protective factor. Of the metalinguistic processes available to readers, morphology, in contrast with phonology, has received noticeably less consideration. Recently, researchers have begun exploring the role of morphological awareness in reading acquisition and reading disabilities. As the English orthography embodies both phonological and morphological information (Chomsky & Halle, 1968), it is reasonable to assume that an explicit awareness of both would be required in the development of adequate reading abilities (Berninger, Abbott, Nagy, & Carlisle, 2010; Deacon & Kirby, 2004; Rastle, Davis, Marslen-Wilson, & Tyler, 2000).

Morphemes, the smallest linguistic units retaining meaning, are combined to form words. Studies have demonstrated an awareness of these units contributes to word recognition, spelling, and reading comprehension, independent of orthographic processing, phonological awareness, RAN, and vocabulary (Carlisle, 2000; Casalis & Louis-Alexandre, 2000; Deacon & Kirby, 2004; Kirby et al., 2012; Roman, Kirby, Parrila, Wade-Woolley, & Deacon, 2009).

Theoretically, there are a number of reasons why MA would be a factor in reading success, and by extension, reading failure. Firstly, the majority of the daily vocabulary individuals are exposed to are morphemically complex with an estimated 60% of the new words acquired by school aged children containing relatively transparent morphological structure (Nagy & Anderson, 1984). Furthermore, many multi-morphemic words in the English language exceed what can be read in a single fixation. It is thought that the decomposition of the morphological structure would enable and speed up processing while reading (Elbro 1989). Support for this has been provided by several priming studies that have suggested the lexicon to be morphologically organized (Diependaele, Sandra, & Grainger, 2005; Feldman, 1991; Leikin & Zur Hagit, 2006). In addition to aiding lexical processing, such segmentation assists in the pronunciation of letter sequences. For instance, segmentation along the morpheme boundary supports the accurate pronunciation of the ‘ea’ in ‘reach’ where it is processed as one phoneme versus the ‘ea’ within ‘react’ which is pronounced separately due to its placement in two adjacent morphemes (Bowers, Kirby, & Deacon, 2010).

Secondly, phonics alone cannot explain many of the linguistic inconsistencies in English, while they may become sensible from a morphological perspective (Nunes, Bryant, & Bindman, 2006). For instance, we do not spell *health* as *helth*, which would be consistent with phoneme-grapheme correspondence rules, but it is written as *health* to maintain the spelling of the root morpheme *heal*.

Lastly, morphemes retain syntactic and semantic information that is thought to aid in the comprehension of new or infrequent words. For instance, an understanding of the base morphemes ‘magic’ and ‘ian’ would help in facilitating in the comprehension of ‘magician’ as referring to a person who produces magic. The syntactic and semantic information provided by the morpheme has been demonstrated to aid in vocabulary acquisition (Nagy, Berninger, & Abbott, 2006; Singson, Mahony, & Mann, 2000; Sparks & Deacon, 2015) and in the reading comprehension of children (Carlisle & Feldman, 1995; Deacon & Kirby, 2004) and adults (Nagy et al., 2006; Wilson-Fowler & Apel, 2015).

As MA is an influential metalinguistic process in literacy achievement, an early deficit in MA could have negative consequences on a child’s reading development. A recent study by Law et al. (in review) has demonstrated a MA deficit in pre-reading children with a family risk of dyslexia. In addition, research has demonstrated the existence of MA deficits in school-aged children and adults with dyslexia when compared with chronologically age-matched controls (Casalis, Colé, & Sopo, 2004; Fowler, Liberman, & Feldman, 1995; Law, Wouters, & Ghesquière, 2015; Shankweiler et al., 1995). However, group differences were not observed when compared with reading-aged controls (Casalis et al., 2004; Elbro, 1989; Fowler et al., 1995).

Yet the relationship between MA and reading may not be so straightforward. A recent study by Deacon et al. (2013) provided evidence that suggested a bidirectional relation between MA and reading.

MA’s early acquisition and development

Studies of pre-reading children have demonstrated that MA is acquired prior to the onset of formal reading instruction (Berko, 1958, Casalis & Louis-Alexandre, 2000; Law et al., 2016). Yet this early attainment is often limited to aspects of inflectional morphology, such as tense markers ‘–ed’ and the simple derivations which do not involve phonological shifts (e.g. ‘jump’ to ‘jumper’) (Berko, 1958; Carlisle & Feldman, 1995). While on the other hand studies have shown that growth in derivational morphology, which is not entirely predictable or transparent, continues after the onset of reading and endures until high school (Nagy, Diakidoy, & Anderson, 1993).

In a study of pre-reading children, Berko (1958) used an oral, non-word completion task that asked children to produce an inflection or simple derivation from a target non-word in order to complete the sentence (i.e. Here is one WUG; now look there are two of them, there are two _____ [WUGS]). Breko noted evidence of an incomplete form of MA at this stage of development due to the fact that children as young as five-years-old were able to complete this task, yet struggled on tasks requiring more complex morphological transformations. Evidence has been provided suggesting that through age and increased print exposure and reading instruction, a child's morphological awareness is expanded due to the introduction of a wider range of morphologically complex words (Berninger et al., 2010; Carlisle & Fleming, 2003; Nagy & Anderson, 1984). In a longitudinal study, Carlisle and Fleming (2003) found that although five to six-year-old children were capable of performing simple morphological decomposition of familiar words they did not possess any explicit knowledge of the lexical or syntactic information contained within the affixes. Yet, Carlisle and Fleming noted that by third grade these skills had progressed. Subsequently, research has demonstrated that MA's independent contribution to literacy outcomes also changes and strengthens over time (Deacon & Kirby, 2004; Singson et al., 2000).

Although MA has been shown to develop with greater print exposure, and its contribution to reading achievement has been exhibited to be independent of PA, early MA acquisition has been shown to be dependent on an individual's pre-reading PA, independent of vocabulary (Carlisle and Nomanbhoy, 1993; Cunningham and Carroll, 2015; Law et al., 2016).

Theoretically, it has been proposed that early phonological awareness aids in the early acquisition of MA. Chiat (2001) argued that as children are exposed to speech in context, they segment the target speech stream into usable phonological components, which are capable of being generalized or related to the context at hand. This mapping between relevant phonological units and contextual cues allows for the formation of generalizable semantic and syntactic units of information and therefore spurs on morphological learning. For instance, the learning of the morpheme *'-ing'*. Early on, children begin to recognize and segment the phonological unit *'–ing'* from speech in addition to taking note of its co-occurrence with generalizable actions which are present in the same context. Through repeated exposure, mappings between speech units and meaning are formed (i.e. "look at the man jumping" while a man is seen jumping) (Law et al. 2016). Studies have demonstrated that more complex phonological shifts between base and derived form are unattainable for many children first learning to read (e.g. divide and division, invade and invasion). Yet, growth in PA and an increased sensitivity to the phonemic structure of language aid in the learning of morphophonemic rules, furthering morphological learning (Carlisle & Nomanbhoy, 1993).

Support of phonology's early influence on MA development has been demonstrated through correlational evidence, for instance by Casalis and Louis-Alexandre (2000) who reported very strong links between pre-reading measures of PA and MA. In addition a study by Cunningham and Carroll (2015) demonstrated pre-reading phonological processing's ability to predict MA in grade one students. More recently a study by Law et al. (2016) found that early MA deficits of children at family-risk of dyslexia could be explained as a function of a co-occurring deficit in PA.

Further support of PA's involvement in MA acquisition has been provided through intervention studies that have demonstrated gains in MA skills through PA instruction in both typically developing kindergarten children and those with speech impairments (Casalis & Colé, 2009; Kirk & Gillon, 2007).

Thus it is reasonable to assume that a pre-reading phonological impairment -typical of children who later are diagnosed with dyslexia- would impede the early acquisition and development of an individual's MA and ultimately impact future reading success.

Questions still remain surrounding the continuity over time of PA's observed influence on MA acquisition during the first years of reading. A recent study by Law et al. (2015) provided evidence of intact MA in some adults with dyslexia in the presence of a PA deficit, indicating MA's potential disassociation with the influence of PA observed earlier in life. The current body of research is lacking in longitudinal studies demonstrating the development of MA starting in the pre-reading phase, through early literacy instruction till the development of decoding skills. As such, it is the aim of this paper to address this gap.

In a longitudinal design, the present study was set out to address questions important in furthering our understanding of children's developing morphological awareness. Early MA acquisition was assessed in relation to both PA and the early development of decoding skills. This research follows up a population of children who were initially described in a previous study that examined pre-reading children with a family risk of dyslexia and no-risk controls (Law et al., 2016). Specifically this paper expands on previous findings by addressing the following questions:

1. Do literacy impaired children show MA deficits prior to formal reading instruction and in the initial years of reading development?
2. Do we see a significant change in MA from kindergarten till grade 2?
3. Does PA make a significant contribution to MA development prior to and after the onset of formal reading instruction?
4. Do decoding skills have an additional influence on MA development above that of PA?

METHODS

PARTICIPANTS

Forty-four primary school children attending the public school system in Ontario, Canada were assessed at three time points as part of our longitudinal study ranging from kindergarten to the beginning of second grade. Initial recruitment involved children fitting into one of two categories, either being at high-risk (HR) for developing dyslexia, or being at low risk (LR). The classification of a child being 'high-risk' was based on the child having at least one first-degree family relative with an official diagnosis of dyslexia. The low-risk control group comprised of children with no family history of reading difficulties.

A parent questionnaire administered upon registration for the study provided information regarding the child's medical history, behaviour and family history of reading and spelling (dis)abilities. In addition, the survey employed the use of the seven point ISCED-scale to access parental educational levels (Unesco, 1997). All participants were found to have an adequate nonverbal IQ as defined by a standard score greater than 85 on the Raven's *Coloured Progressive Matrices* (Raven, 1998). Groups were found not to differ on measures of age, IQ, socioeconomic status (SES) and parental educational level. All children were native English speakers and had exhibited no signs of brain damage or long-term auditory or visual impairments. Groups were later checked and matched for intelligence, gender, age, hyperactivity symptoms, SES and educational environment. Participant characteristics as displayed in Table 1. For a more detailed description of participant recruitment and characteristics see Law et al (2016)).

Table 1: Participant characteristics

	NR (n=23)	LR (n=21)	*p*-value
Gender (F/M)	10/13	10/11	.783[b]
Age in months (mean ± SD)	64.0 ±4.2	62.1±2.8	.078[c]
Non-Verbal IQ[a] (mean ± SD)	109 ± 6.7	107 ± 6.3	.212[c]
Hyperactivity (mean ± SD)	2.7 ± 1.7	3.2 ± 2.3	.461[c]
SES (ISCED) (low/middle/high)	1/13/9	2/12/7	.900[d]
Mother's education (SE/PSE/GS)	3/15/5	4/14/3	.823[d]
Father's education (SE/PSE/GS)	5/13/5	5/13/3	.839[d]

Notes: [a] Scores are standardized (*M* = 100, *SD* = 15). [b] Pearson Chi-Square test. [c] Independent-Samples *t*-test. [d] Fisher's Exact test. SE = secondary school education, PSE = post-secondary education, GS= graduate studies

Materials and Procedures

Socio-economic status (SES).

SES was assessed with the Family Affluence Scale II (FAS II) developed by the World Health Organization (WHO). This measure of family wealth consists of four parts scored as a composite measure ranging from 0-9. Individual scores were transformed into categories ranging from low affluence (0-2), middle affluence (3-5) and high affluence (6-9) as demonstrated in Boyce, Torsheim, Currie, and Zambon (2006).

Decoding

For the creation of the decoding variable we used the word reading and the word attack (non-word reading) subtests from the Woodcock-Johnson III (Woodcock, McGrew, & Mather, 2001). Both subtest scores were normalized using provided grade based norms. The mean of the z-scores from both word reading and non-word reading subtests were used in the creation of a composite score, as both measures were found to be significantly correlated (.825 and .859 in grade 1 and grade 2 respectively).

Spelling

For spelling we used the spelling subtest of the Woodcock-Johnson III (Woodcock et al., 2001). Scores were normalized using grade based norms. Words were presented orally and progressed in difficulty. Standard procedural instructions provided in the Woodcock-Johnson III manual for administration and scoring were utilized.

Letter Knowledge

The letter writing and naming subtests of the *Wide Range Achievement Test* (WRAT3) (Snelbaker, Wilkinson, Robertson, & Glutting, 2001) were used to assess both receptive and productive letter knowledge of the children in kindergarten. The 15 most frequently occurring letters in English language books for children were used for both letter naming and writing.

Phonological awareness (PA)

PA was measured using the phonological awareness subtest of the Clinical Evaluation of Language Fundamentals 4th ed. (CELF-4) (Semel, Wiig, & Secord, 2003). This subtest contained measures of 11 elements: syllable blending (SB), 3 syllable deletion tasks, syllable segmentation (SS), rhyme detection (RD), rhyme production (RP), phoneme blending (PB), initial phoneme identification (IPI), medial phoneme identification (MPI), final phoneme identification (FPI). The rhyme tasks as well as the syllable blending and 2 syllable deletion tasks were excluded from the calculation of PA for first and second grade students due to a high proportion of control subjects reaching ceiling effect. A score of PA was calculated from the total score of all summed subtests.

Verbal short-term memory (VSTM)

VSTM was assessed by using two subtests: *The Number Repetition Subtest* from The Clinical Evaluation of Language Fundamentals 4th ed. (CELF-4) (Semel et al., 2003) and *The Non-word Repetition Test* from the Phonological Assessment Battery (PhAB) (Frederickson, Frith, & Reason, 1997).

The Number Repetition Subtest required the child to immediately recall a series of orally presented digits with lengths of 2 to 9 digits. The test scores were recorded as the total number of correctly recalled lists. A maximum score of 16 was achievable for this test.

The Non-word Repetition Test required each child to repeat orally presented sequences of single syllable nonsense words. Children were required to repeat the sequence correctly. Testing increased in difficulty through a progressive increase in sequence length from 2 to 6. A maximum score of 36 was achievable for this test.

Morphological Awareness

To measure MA we used the Wug test (Breko, 1958) for the first two time points. In the second grade an adapted version of the Wug test was utilized in an effort to minimize potential ceiling effects. The Wug test is a non-word task, developed to evaluate the ability to apply morphological change to mark inflections and derivations. During the test the child is shown a simple picture depicting a creature or activity and is instructed to complete a statement that requires the addition of a suffix to the target pseudo-word: “This is a WUG. Now there is another one. There are two of them. There are two _______.” (Response: WUGS). A maximum score of 33 could have been obtained.

STATISTICAL ANALYSES

All variables were found to be normally distributed as checked by Shapiro-Wilk's test for normality ($p > 0.05$) with the exception of MA at grade 2. In order to approach a normal distribution, this variable was transformed by a logarithmic transformation that led to a distribution that was found to be normal; therefore the transformed scores were used in the analyses. Homogeneity of variance was assessed by Levene's Test for Equality of Variances. Group comparisons were investigated based on an independent-samples *t*-test. The False Discovery Rate (FDR) procedure, a simple sequential Bonferroni-type procedure that has been proven to control for the false discovery rate for independent test statistics was utilized to avoid the likelihood of false positive conclusions (Benjamini & Hochberg, 1995). A two-way repeated measures ANOVA was conducted to determine whether there were statistically significant differences in MA over the three grade levels measures and between reading groups. Concurrent and predictive relationships were evaluated through the use of Pearson correlations to determine the relation between measures of morphological awareness, phonological awareness and literacy. Hierarchical multiple regression including autoregressor controls were used to determine the added value PA and decoding skills had on the prediction of first and second grade MA.

RESULTS

Do literacy impaired children show MA deficits prior to formal reading instruction and in the initial years of reading development?

Subjects were retrospectively divided into two groups—literacy impaired and unimpaired—on their performance on literacy tasks at the start of second grade. Literacy impairment was defined as performing below the 10^{th} percentile on two of the three second grade literacy measures: word reading, spelling or non-word reading. The resulting classification allowed for the creation of a literacy impaired (LI) group consisting of 17 high-risk children and 4 low-risk children; in addition a literacy unimpaired (control) sample of 19 low-risk children was formed. Four children of the original high-risk group were found not to meet the conditions set for the label of literacy impaired. Past research has demonstrated that high-risk normal reading children differed from low-risk controls across many measures, thus it was decided to exclude these individuals from group analysis (Pennington & Lefly, 2001; Snowling, Gallagher, & Frith, 2003).

Tables 2 to 4 presents group differences and performance at each time point of measures of literacy tests, MA and PA. Independent t-tests found no group differences across measures of IQ, age, SES and hyperactivity ($p > 0.05$). No group differences were observed in kindergarten for the measure of letter knowledge.

Phonemic awareness was more heavily weighted in the construction of PA for measures in first and second grade. As many control subjects were found to have achieved a ceiling effect on some syllable level tasks they were removed from the construction of the PA variable. Group differences, assessed by means of an independent samples t-test, were found for both phonological skills VSTM and PA across all time points, with the exception of VSTM in kindergarten (adjusted $\alpha = 0.0375$). Similarly, group differences were found for all literacy measures and morphological awareness at each grade level.

Table 2: Performance and group comparisons on literacy and cognitive tasks in kindergarten.

	Control		LI			
Measure	*M*	*SD*	*M*	*SD*	*t*	*p*
Literacy						
Letter Knowledge^	0.3	0.3	-0.3	1.0	-2.444	.022*
Cognitive Measures						
MA	21.4	4.1	18.4	4.1	-2.281	.028*
VSTM composite	0.2	0.7	-0.3	0.9	-1.922	.062
PA	32.7	4.6	26.4	6.3	-3.535	.001*

Notes. ^ failed Levene's test for Equality of Variance. * significant *p*-value after applying the FDR procedure.

Table 3: Performance and group comparisons on literacy and cognitive tasks in grade 1

	Control		LI			
Measure	M	SD	M	SD	t	p
Literacy						
Decoding	0.3	0.7	-2.2	0.9	-9.261	<.001*
Spelling	112.2	10.5	100.7	6.7	-4.175	<.001*
Cognitive Measures						
MA	23.3	4.0	21.0	3.0	-2.107	.042*
VSTM composite	0.4	0.8	-0.4	0.8	-2.817	.008*
PA	33.9	5.2	23.5	7.9	-4.870	<.001*

Notes. * significant *p*-value after applying the FDR procedure.

Table 4: Performance and group comparisons on literacy and cognitive tasks in Grade 2

	Control		LI			
Measure	M	SD	M	SD	t	p
Literacy						
Decoding	0.9	0.5	-0.8	0.5	-10.462	<.001*
Spelling	105.0	8.5	86.7	7.0	-7.471	<.001*
Cognitive Measures						
MA	26.8	4.0	22.7	4.1	-3.173	.003*
VSTM composite	0.3	0.6	-0.2	0.7	-2.661	.011*
PA	39.2	2.8	29.6	5.9	-6.451	<.001*

Notes. * significant *p*-value after applying the FDR procedure.

CHANGE OF MORPHOLOGICAL AWARENESS ACROSS GRADE LEVEL

Results of the two-way repeated measures ANOVA demonstrated statistically significant differences in MA over the three grade levels measures and between reading groups. There was sphericity for the interaction term, as assessed by Mauchly's test of sphericity ($p > .05$). A main effect of grade was found, $F(2,76) = 23.472$, $p < .001$, partial $\eta^2 = .382$, with MA increasing from kindergarten ($M = 19.82$, $SD = 4.28$) to first grade ($M = 22.10$, $SD = 3.62$) to second grade ($M = 24.65$, $SD = 4.50$). Post hoc analysis with a Bonferroni adjustment revealed that this MA growth was statistically significantly from kindergarten to first grade (a mean difference of -2.26, 95% CI [-4.019, -0.500], $p = .008$), and from kindergarten to second grade (a mean difference of -4.853, 95% CI [-6.65, -3.049], $p < .001$), as well as from first grade to second grade (a mean difference of -2.594, 95% CI [-4.357, -0.831], $p = .001$). A main effect of reading group was observed $F(1,38) = 11.566$, $p = .002$, partial $\eta^2 = .233$, where impaired readers (M= 20.714, SE = 0.630) were found to preform worse on MA when compared with unimpaired readers (M= 23.825, SE = 0.663). There was no statistically significant interaction between grade and reading status, $F(2,76) = .702$, $p = .457$, partial $\eta^2 = .020$.

RELATIONSHIP BETWEEN EARLY LITERACY, PHONOLOGICAL AWARENESS, AND MORPHOLOGICAL AWARENESS

Table 5 shows concurrent and predictive relationships between measures of morphological awareness, phonological awareness, VSTM and measures of literacy. All kindergarten measures were found to be significantly correlated with the exception of relationship between letter knowledge and kindergarten MA and VSTM. Kindergarten MA was found to be significantly related to all measures across first and second grades. However, the same was not found to first grade VSTM. Additionally, MA in second grade was found to be significantly related to all first and second grade variables, with the exception of first grade VSTM. Second grade MA was not found to be related to kindergarten PA and letter knowledge.

To control for the influence of group, partial correlations were conducted across all variables and displayed in the lower left half of Table 5. Kindergarten MA maintained its previously significant relationships with other pre-reading measures. Yet kindergarten MA’s predictive relationships were limited to first and second grade MA and PA and first grade spelling.

Additionally, partial correlations controlling for IQ resulted in the same pattern of findings displayed in table 5.

PREDICTING LATER MORPHOLOGICAL AWARENESS

A hierarchical multiple regression was run to determine if the addition of PA improved the prediction of first grade and then second grade MA over and above age and IQ and autoregressive effects of kindergarten MA. See Table 6 and 7 for full details on each regression model. The full model of IQ, age, kindergarten MA and kindergarten PA to predict first grade MA was statistically significant, $R^2 = .342$, $F(4, 39) = 5.071$, $p = .002$; adjusted $R^2 = .275$. The addition of kindergarten MA to the prediction of first grade MA led to a statistically significant increase in R^2 of .192, $F(1, 40) = 10.367$, $p = .003$. The addition of kindergarten PA to the prediction of first grade MA also led to a statistically significant increase in R^2 of .082, $F(1, 39) = 4.877$, $p = .033$.

The prediction of second grade MA was significantly increased through the addition of kindergarten MA to the model, after controlling for IQ and age, R^2 of .226, $F(1, 40) = 12.321$, $p = .001$. The addition of kindergarten PA to the model did not offer a statistically significant increase in R^2 of .001, $F(1, 39) = 0.039$, $p = .884$. The full model of IQ, age, kindergarten MA and kindergarten PA to predict second grade MA was statistically significant, $R^2 = .268$, $F(4, 39) = 3.567$, $p = .014$; adjusted $R^2 = .193$.

To further understand MA growth during the starting phase of reading instruction, an additional hierarchical multiple regression was run to determine the influence of first grade decoding and PA on the prediction of second grade MA after controlling for age and IQ. The full model of IQ, age, first grade MA, PA and decoding to predict second grade MA was statistically significant, $R^2 = .336$, $F(5, 38) = 3.849$, $p = .006$; adjusted $R^2 = .249$. The addition of first grade PA, prior to reading, did not led to any significant change in R^2 of .040, $F(1, 39) = 2.046$, $p = .161$. After controlling for PA in the model, first grade decoding offered a statistically significant increase in R^2 of .093, $F(1, 38) = 5.321$, $p = .027$. With first grade PA added last into the model, first grade decoding was found to offer a statistically significant increase in R^2 of .133, $F(1, 39) = 7.784$, $p = .008$

Table 5: Pearson correlations between measures of literacy and morphological and phonological awareness across all grade levels

	Kindergarten				Grade1					Grade 2				
Measure	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Kindergarten														
1. VSTM	--	.510***	.345*	.111	.635***	.392**	.237	.371*	.388*	.432**	.347**	.383**	.377*	.252
2.MA	.496***	--	.408**	.180	.250	.454**	.316*	.346*	.438**	.335*	.517***	.429**	.370*	.299*
3. PA	.319*	.338*	--	577***	.324*	.422**	.652***	.644***	.684***	.174	.236	.701***	.648***	.615***
4. LK	.078	.117	.534***	--	.140	.319*	.298*	.417**	.507***	-.064	.193	.372*	.403**	.521***
Grade 1														
5. VSTM	.629***	.181	.227	.063	--	.329*	.375*	.568***	.400**	.441**	.247	.487**	.564***	.483***
6. MA	.374*	.421**	.376*	.278^	.282^	--	.417**	.279^	.438**	.217	.412**	.322*	.308*	.278^
7. PA	.204	.305*	.601***	.233	.303*	.376*	--	.709***	.683***	.273^	.419**	.798***	.716***	.629***
8. Reading	.359*	.241	.550***	.337*	.498***	.195	.673***	--	.707***	.462**	.504***	.867***	.988***	.871***
9. Spelling	.365*	.383*	.636***	.462**	.330*	.398**	.644***	.667***	--	.244	.342*	.716***	.711***	.719***
Grade 2														
10. VSTM	.414**	.266^	.037	-.172	.372*	.154	.178	.339*	.142	--	.447**	.394**	.468***	.328*
11.MA	.328*	.490***	.173	.149	.198	.386*	.383*	.485***	.298^	.411**	--	.415**	.519***	.379*
12. PA	.369*	.348*	.627***	.284^	.398**	.251	.781***	.809***	.675***	.259^	.372*	--	.863***	.767***
13.Reading	.369*	.269^	.554***	.319*	.494***	.230	.686***	.982***	.675***	.343*	.508***	.802***	--	.864***
14.Spelling	.213	.198	.523***	.467**	.398**	.203	.569***	.827***	.675***	.193	.330*	.687***	.819***	--

Note. ^p < .10. *p < .05. **p < .01. ***p < .001.

Table 6: Unique variance in first and second grade MA accounted for by kindergarten PA and MA.

	First Grade MA		Second Grade MA	
	ΔR^2	β	ΔR^2	β
1. IQ	.041	.015	.034	-.012
2. Age	.027	-.277	.007	.013
3. Kindergarten MA	.192**	.380*	.226**	.505**
4. Kindergarten PA	.082*	.333*	.001	.032
Total R^2	.342**		.268*	

Note: R^2, amount of added variance; β, standardized beta

**p* < .05. ***p* < .01. ****p* < .001.

Additionally, regression analysis initially controlling for VSTM in addition to IQ and age resulted in the same pattern of significant findings displayed in tables 6 and 7.

Table 7: Hierarchical regression analyses predicting in second grade MA from intelligence, age, first grade MA (autoregressor) along with first grade PA and decoding.

	Second Grade MA	
	ΔR^2	β
Model 1 (Total R^2 = .336**)		
1. IQ	.034	- .021
2. Age	.007	.052
3. First grade MA	.162**	.312*
4. First Grade PA	.040	- .017
5. First Grade Decoding	.093*	.419*
Model 2 (Total R^2 = .336**)		
4. First Grade Decoding	.133**	.419*
5. First Grade PA	.000	- .017

Note: R^2, amount of added variance; β, standardized beta

**p* < .05. ***p* < .01. ****p* < .001.

Discussion

Morphological awareness has been demonstrated to significantly contribute to later reading and spelling success in both children and adolescent populations. Additionally, intervention studies have shown the positive impact MA instruction has on children and adolescents with dyslexia, as well as it being a potential compensatory mechanism in adults with dyslexia, despite the presence of a PA deficit. For MA to act as such a compensatory measure MA and PA would need to be found as independent; yet recent studies have provided contrary evidence thus supporting phonology's early influence on MA development (Casalis & Louis-Alexandre, 2000; Cunningham & Carroll, 2015; Law et al., 2016).

However, little is still known regarding the early precursors of MA development and the influence early reading acquisition and pre-reading PA deficits have on MA development. Therefore, the present study was set out to address questions related to the acquisition and development of morphological awareness. In a longitudinal design, two groups of children were evaluated, those deemed as literacy impaired and a control group of typically developing children. Initial testing took place prior to the onset of formal reading instruction in kindergarten and was followed up at the start of each academic year, through first and second grades.

Observed MA deficits in individuals with dyslexia are often treated as consequential to the dyslexic reader's poor reading experience, yet evidence from pre-reading children has suggested that observed MA deficits of dyslexic children maybe a direct result of their phonological deficit. The present study's longitudinal pre-reading design allows for the disentangling of this relationship of reading experience and PA and their influence on MA growth.

The results of this study demonstrated that children who were found to be literacy impaired in second grade also had difficulties in morphological awareness prior to reading instruction when compared to the control subjects, thus indicating that poor MA performance is not solely consequential of poor reading experience. Additionally, group comparisons demonstrated that these deficits extend beyond the pre-reading phase and were observed in first and second grades after the onset of formal reading instruction. In addition, PA deficits were found to co-exist with the observed MA deficits across each measurement time point.

Correlational analysis was used to further investigate the relationship between these two variables and found concurrent and predictive relationships between MA and PA throughout these early stages of development. As the pre-reading MA deficit precedes reading instruction, two plausible assumptions can be derived. First, the deficits in pre-reading MA in addition to observed PA deficits could suggest a more general metalinguistic deficit of the literacy impaired group. Alternatively, and theoretically more likely, early MA deficits could be seen as a function of an individual's pre-reading PA. Evidence supporting this theory has been provided by recent studies of pre-reading children (Casalis & Louis-Alexandre, 2000, Cunningham and Carroll, 2015; Law et al., 2016).

In terms of MA growth, a group analysis involving all subjects demonstrated continued positive growth of MA year upon year. A main effect of group was also observed indicating that the better performance of the control subjects was statistically significant. Yet the lack of a significant interaction effect suggests that although the literacy impaired group had poorer performance on the MA task, the development from kindergarten to second grade was similar to that of the control group. Prior to analysis it was theorized that reading acquisition would influence MA development beyond the understanding of inflections obtained in kindergarten. Therefore, as literacy attainment differences were found between groups we had expected to find differences in MA growth patterns from first to second grade as reading instruction began. Yet this was not the case.

To directly evaluate reading skill's involvement in the development of a child's MA, a regression analysis controlling for intelligence, age and the autoregressive effect of previous MA achievement was conducted. Results of our regression analyses revealed PA was only found to make a significant contribution to MA development prior to the onset of reading instruction. The kindergarten measure of PA was found to predict 8.2% of the unique variance of first grade MA, yet was not found to predict any variance in second grade MA. As reading instruction begins PA's initial influence on MA growth diminishes while decoding skills become more influential, as seen in the regression predicting second grade MA.

Prior to the onset of reading instruction a child is involved in the mastery of inflections in addition to basic derivational principles. These early mastered derived forms are primarily phonetically and semantically transparent (e.g. *jump* and *jumper).* As a child's learning of more complex and less phonologically transparent derivations progress, a more explicit awareness of the morphological structure and orthography of words is required. It has been argued that the learning of such irregularities is best acquired through print exposure rather than through spoken language (Casalis & Louis-Alexandre, 2000; Kuo & Anderson, 2006). It maybe that complex morphological representations and an understanding of many derivations only become fully specified through exposure to the written form (Templeton & Scarborough-Franks, 1985) as morphemes are more consistently spelled than they are pronounced (e.g., Bowers & Kirby, Reading and Writing, 2010). Additionally it has been estimated that morphologically complex words compose nearly 40% of the new words encountered by children in text (Nagy et al., 1993; Nagy & Anderson, 1984).

Our results provide evidence of a transition from the influence of pre-reading PA to early decoding skills during morphological awareness's development. These findings suggest one possible directional path where reading can be seen as influencing MA growth. These results, taken together with past correlational and longitudinal research, have demonstrated the opposite situation where MA has been found to predict later reading achievement (Carlisle, 2000; Deacon & Kirby, 2004; Kirby et al., 2012; Roman et al., 2009) which offers support for the bi-directional relationship between word reading skills and MA proposed by Deacon, Benere, and Pasquarella (2013). Specifically, our results assist in supporting Deacon's claim that morphological awareness is partly obtained through reading accuracy.

The presence of a bi-directional relation between MA and early reading skills may be detrimental for dyslexic children, specifically those whose reading problems predominantly stem from a PA deficit. Pre-reading PA has been demonstrated in past research to be a predictor of early reading acquisition (Bradley & Bryant, 1983; Kirby et al., 2003; Melby-Lervåg et al., 2012) and early MA development (see the results of this study in addition to Casalis & Louis-Alexandre, 2000, Cunningham and Carroll, 2015; Law et al., 2016). In the case of a child with a pre-reading PA deficit a situation could arise where both MA and early literacy attainment would be negatively impacted. In the presence of a bi-directional relationship between MA and early reading skills such a situation could theoretically establish a negative feed-back loop. Theoretically, an individual's poorly developed MA skills would negatively impact their early reading growth, while poor reading would potentially limit their MA growth.

The results of this study has demonstrated the existence of early MA deficits in literacy impaired children and support the need for adequate MA intervention and explicit instruction for at risk children within the early stages of literacy instruction.

Educational implication

Intervention studies involving morphological awareness have provided evidence that training in morphological awareness increases reading skill in English (Bowers et al., 2010; Carlisle, 2010; Goodwin & Ahn, 2010). Such evidence has demonstrated the potential value of explicit instruction of morphemes to children. Our results have demonstrated the existence of a pre-reading MA deficit in children later found to be literacy impaired. Such findings indicate that these impaired children do not only approach learning to read with a deficit in their phonological skills but also their morphological knowledge. Thus indicating the need of earlier explicit teaching of morphemes to children to aid in reducing any negative influence such an early MA deficit could have on literacy development and attainment.

Limitation

There are several limitations to our work. The participants selected for the purposes of this study were recruited on voluntary bases solicited through flyers sent home with the child from school. It could be argued that such a recruitment method could yield a higher concentration of educationally motivated parents or parents concerned about their child's literacy success. Moreover, also the relatively small sample size of this study could potentially limit the extent to which the findings can be generalized. Additional limitations emerge from the measures included in our study. The Wug task, a pseudo-word task, was used to rule out any effect from root word familiarity (i.e. vocabulary). It could be argued that a more correct mean of reducing the potential confounding of vocabulary in the assessment of morphological awareness would be to introduce a measure of vocabulary as a covariate. Yet, an intrinsic relationship between morphological awareness and vocabulary exists (Spencer et al., 2015). Therefore controlling for the variance of performance on a vocabulary measure would remove a substantial proportion of the expected relationship between reading and morphological awareness (Kuo & Anderson, 2006). Therefore, to reduce such a loss, this study was limited to the degree in which variance in vocabulary could be controlled for within our predictive models. Although it is worth noting that similar studies such as Cunningham and Carol (2015) prediction of morphological awareness was found to be independent of vocabulary.

Lastly, our study is limited in our conclusions and discussion regarding the bi-directionality of the MA and word reading as the goal of this study was to evaluate the growth of MA and reading's influence on that growth. An analysis of MA as a predictor of word reading was not presented within this study due the lack of morphological complex target words presented within the non-word and word reading tasks. As the tasks were designed to progressively increase in difficulty most children were not presented with any target reading word containing any morphological complexity. As a result, it would be difficult to conclude that any variance MA would potentially predict of the reading variable would not be due to the application of morphological awareness during the reading task. Future research would benefit form the addition of specially designed word reading lists containing morphologically complex words at suitable difficulty levels to allow for a better assessment of MA's relationship in word reading.

Future research in morphological awareness development and it's association with literacy outcomes could benefit from an increased sample size as well as the inclusion of a wider array of control variables to account for any possible influence of a third variable. Although our study took great care in controlling for group differences in educational environment, parental education and SES background the observed associations of this study could possibly be due to an unmeasured third variable such as a child's language environment at home, vocabulary or orthographic knowledge. Yet it is worth noting that in this respect all research involving associations between variables has this limitation.

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CHAPTER 7

General conclusions and future perspectives

The aim of this dissertation was twofold. First we set out to examine, whether morphological awareness (MA) should be considered as a unique risk and/or protective factor in relation to the literacy outcomes of children and adults with dyslexia. Additionally, this project aimed to investigate the presence and nature of auditory temporal processing deficits in persons with dyslexia. As such, the relation between fine-grained auditory processing measures and the ability to predict concurrent and future phonological awareness (PA) and literacy outcomes was assessed and discussed. In order to evaluate any developmental and/or causal influence of either morphological awareness or auditory measures, we studied a population of pre-reading children with and without a family risk of dyslexia and followed them through the early stages of literacy development. To understand how these variables were represented later in life and contributed to later literacy achievement, an adult population was additionally assessed.

THEORETICAL AND EDUCATIONAL RELEVANCE

AUDITORY TEMPORAL PROCESSING AND DYSLEXIA

Using a child and an adult population, we empirically evaluated the auditory temporal processing deficit theory of dyslexia. This theory postulates that an underlying deficit in low-level auditory temporal processing interferes with accurate detection of speech specific acoustic cues. Consequently, it is thought that the resulting disruption of speech perception enables a cascade of effects negatively impacting the development of the initial mapping of speech sounds onto their corresponding graphemes, resulting in the creation of the behavioural traits of poor word reading and spelling that are associated with dyslexia (Boets, Wouters, Van Wieringen, & Ghesquière, 2006; Farmer & Klein, 1995; Habib, 2000; Tallal, 1980). Based on this theory several assumptions were made: first, it was expected that when compared with controls, individuals with dyslexia would exhibit auditory processing deficits and speech perception problems along with phonological problems. Additionally, it was assumed that significant relations between each of these variables, along with literacy achievement, would be observable. Lastly, it was assumed that the same processes influencing the development of the expressed literacy impairments of individuals with dyslexia should also be observed in normal literacy development. Therefore, similar to the dyslexic population, we expected to observe similar interrelations of the target variables within the general population.

Support for these assumptions were provided from both child and adult studies as reported in this dissertation (see chapters 2, 4 & 5). The results presented in this dissertation show the presence of an auditory temporal processing deficit within the dyslexic population. In addition, findings across all age groups supported the existence of a very specific deficit confined to speech envelope cues rather than to the fine structure of the speech waveform represented within the FM detection task. At all assessed time points performance on RT discrimination tasks were found to be significantly related to phonological awareness measures as well as to literacy measures, thus implicating the same processes influencing literacy development within both normal reading and reading impaired populations.

In addition to the assessment of the aforementioned assumptions, this dissertation set out to investigate the directionality inherent in the auditory temporal processing deficit theory. Although the theory predicts a specific cascade of effects from auditory processing to reading, research has suggested that basic auditory processing may be influenced from top-down processes, such as poorly specified phonemic representations and poor reading experiences (Bishop, Hardiman, & Barry, 2012; Mayo, Scobbie, Hewlett, & Waters, 2003; Nittrouer & Miller, 1997).

As most studies have been centered at a single time point, in populations of adults and school-aged children from the start of literacy instruction (e.g., Hämäläinen, Salminen, & Leppänen, 2013), questions of directionality and causality are difficult to address. As discussed in earlier chapters of this dissertation, only a few studies have investigated pre-reading children longitudinally, thus providing evidence of directionality. For instance, chapter 5 of this dissertation discussed a study by Boets et al. (2011) that retrospectively explored the auditory temporal processing deficit theory in a population of pre-reading children who later developed dyslexia. In this study, Boets and colleagues found evidence supporting a pre-reading auditory processing deficit specific to slow-rate FM sensitivity. These pre-reading measures were found to uniquely predict later growth in reading. Yet the lack of significant partial cross-lagged correlations prevented any reliable interpretation of directionality, leading Boets and colleagues to conclude a probable bidirectional relationship between auditory processing, speech perception and phonological awareness.

Contrary to the study of Boets et al. (2011) evidence suggesting directionality was observed within this research. Results reported in chapters 4 and 5 indicate that an observed auditory temporal processing deficit is not consequential to the expressed literacy problems of individuals with dyslexia, as RT discrimination deficits were observed in both high risk and dyslexic children prior to formal reading instruction. Additionally, the retrospective analysis reported in chapter 5 demonstrated the concurrent and predictive relation between pre-reading RT with phonological awareness. Regression analyses further demonstrated pre-reading RT and FM's unique ability to predict variance in first and second grade reading. These findings suggest that the impact of basic auditory processing skills on reading development is not limited to a time point prior to reading instruction but extends through early stages of reading development, thus highlighting auditory processing's role in early reading development. Additionally, the results of this dissertation support the idea that individual differences in auditory processing are not simply a consequence of phonological awareness and early literacy achievement, offering insight into the question of directionality and supporting the theorized cascade effect predicted by the auditory processing deficit theory. Yet it is worth noting that results of both child (see chapter 4 & 5) and adult (see chapter 2) studies were not able to support previous findings of FM deficits in behavioural studies in pre-school children (Boets, Ghesquière, Van Wieringen, & Wouters, 2007) and adults (Heath, Bishop, Hogben, & Roach, 2006; Witton, Stein, Stoodley, Rosner, & Talcott, 2002).

In addition to its theoretical importance, this body of work also has educational implications for early intervention. A recent intervention study of school-aged children with dyslexia which set out to improve RT discrimination demonstrated significant direct effects upon the children's rhyming skills in comparison to a no-intervention control group (Thomson, Leong, & Goswami, 2013). Taken together with our findings of pre-reading RT's relation to precursor reading skills as well as pre-reading RT's ability to predict variance in first and second grade reading, this type of intervention may be more effective at the pre-reading stage.

Although measures of auditory processing were able to significantly contribute to the overall model in predicting literacy outcomes, in both our adult and child study a large proportion of reading (problems) still remains unexplained. In this way, the findings of this dissertation cannot support a single deficit model of dyslexia as proposed by the auditory processing deficit theory. Our results suggest that a multifactorial approach should be explored to fully identify the mechanisms underlying dyslexia. By investigating alternative cognitive factors, such as orthographic or morphological processing (Bekebrede, van der Leij, & Share, 2009), alternative perceptual factors (Stein, 2001) and biological explanations (Nicolson, Fawcett, & Dean, 2001), the variance and comorbid symptoms associated with the dyslexic population can be better understood.

Speech perception

Due to slow-rate dynamic auditory cues abundance in speech, it was hypothesized that a deficit in processing speech specific auditory cues, such as RT, would ultimately lead to a disruption in speech perception. Fitting with the auditory processing deficit theory of dyslexia, it was additionally assumed that measures of speech perception would be found to relate to both auditory perception and phonological measures.

Although evidence of a slow rate auditory processing deficit was found in both our studies of children and adults, we were not able to demonstrate any evidence to support the existence of a speech-perception deficit. These results are contrary to past research (Boets et al., 2007; Bradlow, Kraus, & Hayes, 2003; Snowling, Goulandris, Bowlby, & Howell, 1986; Wible, Nicol, & Kraus, 2002; Ziegler, Pech- Georgel, George, & Lorenzi, 2009). In addition, speech-in-noise measures were found to be unrelated to any measure of phonological awareness or literacy.

Three possible explanations can be made to explain these results. First, specific task characteristics might have contributed to the lack of findings. As discussed in chapter 2, the lack of group differences may have been a function of the stationary speech weighted background noise used as a speech mask. Dole, Hoen, and Meunier (2012) noted that such masking noises are less effective in differentiating between dyslexic and normal readers than modulated noises and background speech masks. An alternative interpretation can be that slow-rate auditory processing either independently relates to reading measures or relates through phonological awareness and not through speech perception measures. However, this remains unlikely considering the prevalence of slow-rate dynamic auditory cues in the speech signal. Nevertheless, a more plausible explanation may be related to the developmental time point assessed within this body of research. Discussed in chapter 5, it was suggested that the theorized developmental link between auditory processing and speech perception might diminish with age due to the effect of different developmental influences over time. Thus, the inability to discover a relationship between these measures may be a result of the age at which these measures were assessed. Therefore the association between these variables may lay at earlier stages of development as it has also been reported to exist in infancy (Leppänen et al., 2010).

MORPHOLOGICAL AWARENESS AND DYSLEXIA

Results of this dissertation were in line with past research in that a single phonological awareness deficit or an auditory processing deficit was not sufficient to produce the behavioural symptoms associated with dyslexia, thus supporting a multi deficit model of dyslexia. As discussed in the first chapter of this dissertation, a multi deficit model of dyslexia predicts various factors working together probabilistically as risk or protective factors that result in the development of the expressed behavioural symptoms attributed to dyslexia. Within the context of this theory, morphological awareness's potential role as a protective and risk factor was evaluated within this dissertation. As discussed in chapter 1, morphological awareness has been described to theoretically have the potential to act as both a risk and/or protective factor.

Morphological awareness's contribution to reading outcomes in both children and adults has been well established. Therefore the existence of a morphological awareness deficit in dyslexic readers would have the potential to increase the liability of the observed literacy deficits associated with dyslexia. While on the other hand, it was noted in chapter 3, for morphological awareness to theoretically act as a protective factor it would need to be found relatively intact and independent from phonological awareness. Recent studies, however, have provided evidence supporting the early influence of phonological awareness on morphological awareness development, thus calling into question morphological awareness's independence and potential to act as a compensatory/protective factor (Casalis & Louis-Alexandre, 2000; Cunningham & Carroll, 2015). To understand the relation between morphological awareness and phonological awareness, we evaluated morphological awareness development prior to formal reading instruction and through early reading development. Additionally, morphological awareness's role as a protective factor was examined within populations of compensated and non-compensated adults with dyslexia.

Results from both our adult and child studies demonstrated poorer performance on morphological awareness tasks from individuals with dyslexia when compared to the control subjects. The fact that these deficits were observed in pre-reading children suggests that these deficits are not solely the consequence of poor reading experience. In addition, morphological awareness deficits were found to exist in parallel and were related with the phonological awareness deficits of individuals with dyslexia at each time point measured. Given past research demonstrating the influence of morphological awareness on later literacy achievement, the discovery of morphological awareness deficits across age groups could be interpreted to implicate morphological awareness as a potential risk factor, in conjunction with phonological awareness deficits. Two plausible assumptions could be derived from these findings. First, the deficits in pre-reading morphological awareness in addition to observed phonological awareness deficits could suggest a more general metalinguistic deficit in the literacy impaired group which could be said to be the cause of both morphological awareness and phonological awareness deficits. Yet results reported in chapter 4 did not support this conclusion and instead supported an alternative hypothesis: that early morphological awareness deficits are a function of an individual's pre-reading phonological awareness impairment. These findings have been corroborated by past research that has demonstrated the early dependence of morphological awareness on phonological awareness (Casalis & Louis-Alexandre, 2000; Cunningham & Carroll, 2013).

Theoretically, in order for morphological awareness to act as a protective or compensatory measure, morphological awareness would have to be found relatively intact and independent from phonological awareness, as mentioned earlier. Yet, early findings from our pre-reading sample suggested this was not the case: morphological awareness deficits were observed to be dependent on phonological awareness. Nevertheless, these results may have been related to the developmental stage of the children assessed. For instance the regression analysis from the retrospective longitudinal study reported in chapter 6 revealed the diminishing contribution of phonological awareness to the growth of morphological awareness. Phonological awareness was only found to make a significant contribution to morphological awareness development prior to the onset of reading instruction. Results demonstrated that from the onset of reading instruction, the initial influence of phonological awareness on morphological awareness growth diminished while decoding skills became more influential. The results of phonological awareness's diminishing influence on morphological awareness, taken together with findings form intervention studies (Bowers, Kirby, & Deacon, 2010; Carlisle, 2010; Goodwin & Ahn, 2010), suggests the potential for morphological awareness to act as a protective or compensatory factor for children and adults. Results from our adult study reported in chapter 3 supported this idea, as the morphological awareness skills of compensated adults with dyslexia were found not to differ from normal reading controls while being significantly stronger than their non-compensated counterparts. In support of past research (i.e. Elbro & Arnbak, 1996), it was concluded that intact and strong morphological awareness skills observed in the adult population is associated with the achieved compensation of these dyslexics.

To theoretically explain morphological awareness's function as a compensatory variable, it was postulated that adults with dyslexia might had made a shift in the underlying cognitive mechanisms of word reading. When results of the regression analysis between both sample groups reported in chapter 3 were compared, the dyslexic group exhibited a shift away from an association between phonological skills and word reading to a greater involvement of morphological awareness, which was not observed in the control sample. The nature of written morphemes, as discussed by Taft (2003), allows for the segmentation of morphologically complex words into their constituent parts (base, prefix and suffix), enabling an alternative path of sub-lexical processing, which is thought to be impeded in individuals with dyslexia as a result of their observed phonological deficit. Thus, a relative strength in morphological awareness could theoretically facilitate word reading by minimizing dependence on phonological processing through the alternative path of sub-lexical processing.

Additionally, research within this dissertation provides support for the proposed bidirectional relation between reading and morphological awareness (Deacon, Benere, & Pasquarella, 2013). As noted earlier, an abundance of past research has demonstrated the contribution of morphological awareness to literacy outcomes throughout life (Carlisle, 2000; Deacon & Kirby, 2004; Roman, Kirby, Parrila, Wade-Woolley, & Deacon, 2009). However, the research presented in this dissertation is one of the few longitudinal studies to provide direct support for the influence of reading on morphological awareness development. Thus, this dissertation offers new support for the bi-directional relation between morphological awareness and reading. The support of a bidirectional relation is theoretically important because it demonstrates the potential impact that poor reading experience has on morphological awareness growth and vice versa. Therefore it is reasonable to assume that poor morphological awareness skills—a consequence of a dyslexic reader's pre-reading phonological awareness deficit—could potentially exacerbate, and increase the liability of the development of the reading impairment typical of individuals with dyslexia. With the knowledge of an existing bidirectional relationship between morphological awareness and reading, we could now expect these early reading impairments of children with dyslexia to disrupt future growth in morphological awareness, creating a negative feedback loop.

In summary, the evidence reported in this dissertation has demonstrated that reading disabled children approach initial reading instruction with both phonological awareness and morphological awareness deficits. After the onset of reading instruction, the influence of phonological awareness on morphological awareness growth diminishes, as decoding skills become a greater predictor of morphological awareness growth. For many children with dyslexia, morphological awareness deficits will persist, impeded by their poor reading experience. However, for some, the morphological awareness achievement gap may be bridged—whether through direct morphological awareness instruction or reading interventions schemes—allowing for morphological awareness to act as a potential protective factor. These findings suggest and support the need for targeted phonological awareness training prior to reading instruction for high-risk children and also the need for targeted intervention schemes focusing on morphological awareness development at the point of initial reading instruction.

LIMITATIONS OF THE STUDY

Several limitations regarding our work are worth noting. First, the generalizability of the findings reported in this dissertation may be restricted due to the limited sample size of each study. For instance, conclusions reported in both chapters 5 and 6 were based on a sample size of only 21 literacy impaired children. Additionally, the restricted sample size limited the statistical analysis we performed. A larger sample size would have permitted the use of structural equation modeling to allow for an analysis of the causal paths of the model we were investigating. In addition, a potential and inadvertent selection bias within both adult and child samples may have existed. For instance, the adult population reported in chapters 2 and 3 relied solely on the inclusion of university students. Due to the achieved academic level, this sample population's cognitive skills and literacy levels may not be representative of the general population. Secondly, it could be argued that for young adults with dyslexia to achieve the level of educational proficiency required to enter university, varying levels of compensation would be present in this specific group. Such relative cognitive strengths and compensation processes could have resulted in the underrepresentation of the percentages of observed deviant performance on slow-rate dynamic auditory processing tasks and phonological awareness measures (i.e., Stoodley, Hill, Stein, & Bishop, 2006).

In the case of the child population, sampling bias may have occurred during the recruitment. As enrolment for the study relied on parental responses to flyers sent home with children and did not involve a general sample, it could be argued that educationally motivated parents or parents concerned about their child's literacy success may had been more inclined to respond. The avoidance of this potential sampling bias was not possible due to restrictions placed on the solicitation of parent involvement by the school administration. The collection of a general sample of an entire class was not permitted.

The case for additional limitations could be argued regarding the measures included in our study. For instance, within the child study, to control for the effect of root word familiarity (i.e. vocabulary), a pseudo-word task was used called the Wug task. There are grounds to believe that the introduction of a more directly assessed vocabulary measure as a covariate would have more effectively reduced the potential confounding of vocabulary in the morphological awareness assessment. Yet, due to an intrinsic relationship between morphological awareness and vocabulary, using a control for the variance of performance on a vocabulary measure could have potentially eliminated a substantial proportion of the expected relationship between reading and morphological awareness (Kuo & Anderson, 2006). To reduce such a loss, the indirect control of vocabulary offered through the pseudo-word Wug task was selected for the purposes of our research. It is worth noting that there is evidence that the addition of vocabulary to the prediction model of morphological awareness may not have altered our findings greatly as a study by Cunningham and Carroll

(2015) reported that the prediction of morphological awareness was found to be independent of vocabulary.

An additional limitation could be perceived in the lack of an instrument for the direct assessment of attention problems of participants. Although the parental questionnaire in the child study screened for potential hyperactivity or behavioural problems using questions taken from the Strengths and Difficulties Questionnaire (SDQ) (Goodman, 2001) assessment of attention in first and second grades was not conducted. Similarly the adult study relied upon self-reporting attention struggles during the initial intake questionnaire, yet no dyslexic subjects were excluded from the study based on the demonstration of attention deficit symptoms. The rational for this decision was motivated by our attempt to have our samples be as representative as possible of individuals with dyslexia. It could be argued that such a lack of direct control of attention differences could impact results in the psychophysical testing reported in chapters 2, 4 and 5. As psychophysical testing demands sustained attention from participants, it has been suggested that sensory deficits observed in individuals with dyslexia may be a function of a general difficulty with task completion, or be related to the higher rates of attention-related disorders in this population (Hulslander et al., 2004; Roach, Edwards, & Hogben, 2004; Stuart, McAnally, & Castles, 2001; Willcutt & Pennington, 2000). To mitigate this problem, we employed a measure of intensity discrimination (ID) as an indirect control of any potential task-related demands. Group differences between typical and dyslexic readers are often not found in measures of ID (see Hämäläinen, Salminen, and Leppänen, 2013). Since group differences on the ID measure were not found and both the ID and other auditory processing measures were equal in design and methodology, we were permitted to rule out any task-related demands, attention, and cognitive aspects as driving factors of observed auditory problems. In the case of the adult population where group differences were observed, ID was introduced as a control variable within the statistical analysis.

FUTURE PERSPECTIVES

Reading is a process that develops over time and requires a multitude of prerequisite skills that evolve and develop over several years before and after the onset of formal reading instruction. Therefore, it is reasonable to assume that an individual's sensory skills and their association with precursory reading skills also change and develop overtime. In the case of individuals with dyslexia, it is reasonable to expect that the manifestation of sensory impairments, such as the RT discrimination deficit observed in this collection of studies, would also change over the course of time. For instance, it has been shown that the importance of phonological awareness as a predictor of literacy outcomes diminishes with age (de Jong & van der Leij, 1999; Kirby, Parrila, & Pfeiffer, 2003), and thus it could be posited that the observed influence of a pre-readers' RT deficit and morphological awareness may also diminish. As most longitudinal studies involving pre-reading children are limited to a time scale of only a few years after the onset of reading, further follow up of this child population could help broaden our understanding of the developmental trajectory and influences of these deficits.

Additionally, due to the lack of significant group differences and relations between our measures of speech perception and auditory processing, we were not able to fully support the theoretical cascade effect predicted by the auditory deficit theory of dyslexia. As a result, it was hypothesized that this lack of association between these variables may be related to the developmental stage assessed within this research. Previous infancy studies have provided evidence of this association occurring early on in development, which suggests that the association may diminish with age (Leppänen et al., 2010). Therefore, it would be beneficial to investigate from infancy, in a longitudinal format, auditory processing, speech perception abilities and language development.

Evidence presented in chapter 3 supported the theory of morphological awareness functioning as a compensatory variable for some adults with dyslexia. Additionally, it was postulated that for morphological awareness to act as a compensatory factor, some adults with dyslexia had made a shift in the underlying cognitive mechanisms of word reading away from an association between phonological skills and word reading to a greater reliance on morphological awareness. It was suggested that dyslexic readers exploited the morphological structure by segmenting words into their constituent morphemes to aid in sub-lexical processing. Such a shift in the underlying cognitive mechanisms of reading could help minimize dependence on phonological processing during sub-lexical processing. Recent studies of morphological processing have extended beyond behavioural psycholinguistics to the use of neuroimaging techniques. Such advancements have provided neuroanatomical evidence suggesting that morphology is an automatic and distinct aspect of visually processing words. Several studies across different languages have implicated the inferior frontal gyrus (IFG) in morphological processing (Bick, Frost, & Goelman, 2010; Bozic, Marslen-Wilson, Stamatakis, Davis, & Tyler, 2007; Tyler & Marslen-Wilson, 2008; Tyler, Marslen-Wilson, & Stamatakis, 2005). To date, very few studies have investigated the neural basis of morphological processing differences in individuals with dyslexia. Future neuroimaging studies could examine morphological processing and its potential neural signatures related to compensation. In doing so, researchers can offer new insights into dyslexia compensation, which may lead to the development and design of target intervention schemes.

As demonstrated in our adult population, some adults with dyslexia are able to recover from the earlier expressed deficits in word reading accuracy and reading comprehension (i.e., Lefly & Pennington, 1991). Given the strong relationship between spelling accuracy and word reading in typically developing readers (i.e., Ehri 2005), it would be reasonable to assume that the reading gains of individuals with dyslexia would translate into gains in spelling. Evidence provided in chapter 3 supported past research in demonstrating that, regardless of the level of reading compensation achieved, there often remain residual deficits in spelling accuracy (Berninger, 2006; Kemp, Parrila, & Kirby, 2009). Although dyslexia is often characterized as both word reading and spelling difficulties (Vellutino, Fletcher, Snowling, & Scanlon, 2004), much of the research surrounding dyslexia has focused on word reading alone. Pennington and colleagues (1986) theorized that adults with dyslexia would be able to overcome their initial spelling deficits through the application of specific orthographic rules and the greater consistency offered by morphemes and larger orthographic units. A natural future extension of our findings relating to morphological awareness and compensation would be to evaluate the role and use of morphological awareness in the spelling skills and strategy development of individuals with dyslexia.

The identification of the underlying cognitive mechanisms of the residual spelling problems of adults with dyslexia would enable the development of targeted support services and interventions to better support those who still struggle.

Building on past research, this collection of manuscripts has contributed to our understanding of dyslexia, yet a great deal still remains to be discovered. With each new advancement and answer to previous unknowns, we come one step closer to a better understanding of dyslexia, whilst simultaneously revealing the need for further research.

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